AD-A195 159 CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH(U) 1/1
ROCHESTER UNIV NY INST OF OPTICS N GEORGE 01 FEB 88
ARO-24626.33-PH DAAL03-86-K-0173

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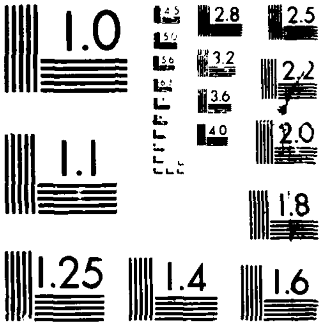

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): ARO 24626.33-PH
6a. NAME OF PERFORMING ORGANIZATION: University of Rochester; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: U. S. Army Research Office
6c. ADDRESS (City, State, and ZIP Code): Institute of Optics, Rochester, New York 14627	7b. ADDRESS (City, State, and ZIP Code): P. O. Box 12211, Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: U. S. Army Research Office; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: DAAL03-86-K-0173
8c. ADDRESS (City, State, and ZIP Code): P. O. Box 12211, Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Center for Opto-Electronic Systems Research

12. PERSONAL AUTHOR(S)
Nicholas George

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Progress	FROM 10/1/86 TO 12/31/87	February, 1988	63

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The primary goal of the **Center for Opto-Electronic Systems Research** is to contribute fundamental scientific knowledge which is relevant to opto-electronic systems with an emphasis on key technology areas common to these systems, e.g., lasers, modulation, optical systems design, propagation and coherence, detection theory, signal processing, digital methods, and display. Progress for the year (1987) is described in this report grouped into three main sectors: **Sources and Sensors**; **Signal Processing and Image Understanding**; and **Optical Systems Design**. The professional staff includes 12 faculty principal investigators together with 21 doctoral scholars. Listings are provided separately of publications resulting from the research, faculty visits to Army laboratories for technology interchange, brief outlines of the major research findings, and Abstracts of the publications.

Keywords: Electrooptics,

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Nicholas George	716-275-2417	

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

24626-PH-UIR

PROGRESS REPORT

1. **ARO PROPOSAL NUMBER:** 24626-PH-UIR
2. **PERIOD COVERED BY REPORT:** 1 October 1986 - 31 December 1987
3. **TITLE TO PROPOSAL:** Center for OPTO-ELECTRONIC SYSTEMS RESEARCH
4. **CONTRACT OR GRANT NUMBER:** DAAL03-86-K-0173
5. **NAME OF INSTITUTION:** University of Rochester
6. **AUTHORS OF REPORT:** Nicholas George, Program Director

CONTENTS **PAGE**

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

7.1 Sources and Sensors

"Interference pattern produced on reflection at a phase conjugate mirror. Part I. Theory," E. Wolf, L. Mandel, R.W. Boyd, T.M. Habashy, and M. Nieto-Vesperinas, J. Opt. Soc. Am. B **4**, 1260-1265 (1987).

"Interference pattern produced on reflection at a phase conjugate mirror. Part II. Experiment," Arturo A. Jacobs, Wayne R. Tompkin, Robert W. Boyd, and Emil Wolf, J. Opt. Soc. Am. B **4**, 1266-1268 (1987).

"Instabilities and chaos in the polarizations of counterpropagating light fields," Alexander L. Gaeta, Robert W. Boyd, Jay R. Ackerhalt, and Peter W. Milonni, Phys. Rev. Lett. **58**, 2432-2435 (1987).

"Optical emission from impurities within an epitaxial-silicon optical waveguide," T.G. Brown, P.L. Bradfield, D.G. Hall, and R.A. Soref, Opt. Lett. **12**, 753-755 (1987).

"Optical waveguides in oxygen-implanted buried-oxide silicon-on-insulator structures," B.N. Kurdi and D.G. Hall, Appl. Phys. Letters **51(Feb)**, xxx-yyy (1988).

"Competition between four-wave mixing and amplified spontaneous emission," M.S. Malcuit, D.J. Gauthier, and R.W. Boyd, in **Hyperfine Interactions**, J.C. Baltzer A.G. Scientific Publishing Company, pp. xxx-yyy (1988).

"Quantum theory of Rabi sideband generation by forward four-wave mixing,' G.S. Agarwal and R.W. Boyd, submitted to Physical Review A.

"Laser instabilities," C.R. Stroud, Jr., to be published in Proceedings of the Twelfth International Nathiagali Summer College on Physics and Contemporary Needs, Nathiagali, Pakistan, 18 June - 9 July 1987.

"Transients in the micromaser," C.R. Stroud, Jr., to be published in Proceedings of the Twelfth International Nathiagali Summer College on Physics and Contemporary Needs, Nathiagali, Pakistan, 18 June - 9 July 1987.

"Near-infrared dichroism of a mesogenic transition metal complex and its solubility in nematic hosts," K.L. Marshall and S.D. Jacobs, accepted for publication in Molecular Crystals and Liquid Crystals.

"A reexamination of the synthesis of liquid crystalline side-chain polyacrylates via liquid-liquid phase transfer catalysis," S.H. Chen and Y.F. Maa (S. Jacobs), accepted by Macromolecules.

"The preparation of liquid-crystalline side-chain polyacrylate by chemically modifying poly(sodium acrylate) in hexamethylphosphoramide," S.H. Chen and Y.F. Maa (S. Jacobs), submitted to Macromolecules.

"Above-threshold ionization with femtosecond pulses: a comparison of quantum and classical predictions," Jonathan Parker and C. R. Stroud, Jr., submitted to Physical Review Letters.

"Transient absorption by a Rydberg atom in a resonant cavity," Mark Mallalieu, Jonathan Parker, and C. R. Stroud, Jr., submitted to Physical Review A.

"Amplitude-stabilized chaotic light," C. Radzewicz, Z. W. Li, and M. G. Raymer, submitted to Physical Review A.

7.2 Signal Processing & Image Understanding

"Sine-cosine cascade correlator with real-valued filters," Shen-ge Wang and Nicholas George. Opt. Lett. **12**, 383-385 (1987).

"Diffraction from a circular aperture: on-axis field strength. R. Edward English, Jr. and Nicholas George. Appl. Opt. **26**, 2360-2363 (1987).

"The instantaneous cross-spectral density of non-stationary wavefields," Brian Cairns and Emil Wolf, Opt. Comm. **62**, 215-218 (1987).

"Spectral shifts produced by source correlations," Dean Faklis and G.M. Morris, Opt. Lett. **13**, 4-6 (1988).

"Spectral modulation by control of source correlations," Avshalom Gamliel and Emil Wolf, Opt. Comm. **65**, 91-96 (1988).

"White light interferometry with an achromatic phase shifter," Nicholas George and Thomas Stone, submitted to Proc. Soc. Photo-Opt. Instr. Eng. **883**, xxx-yyy (1988).

"Diffuser radiation patterns over a large dynamic range," Lyle G. Shirley and Nicholas George, accepted for publication in Applied Optics.

"Diffraction patterns in the shadows of disks and obstacles," R. Edward English, Jr. and Nicholas George, submitted to Applied Optics.

"Generation and statistical properties of optical dead-time effects," Doo Jin Cho and G. Michael Morris, submitted to the Journal of Modern Optics.

"Pattern recognition using photon-limited images," G. Michael Morris. Chapter in a book on **Optical Computing and Processing**. To be published by Academic Press. Henri Arsenault and Tomasz Szoplik are editors.

"Changes in the spectrum of partially coherent light beam propagating in free space," Zagorka Dacic and Emil Wolf, submitted to the Journal of the Optical Society of America A.

7.3 Optical Systems Design

"Radial gradient-index eyepiece design," John P. Bowen, J. Brian Caldwell, Leo R. Gardner, Niels Haun, Michael T. Houk, Douglas S. Kindred, Duncan T. Moore, Masataka Shiba, and David Y.H. Wang, submitted to Applied Optics.

"Optical System Assessment. I," G. W. Forbes, submitted to the Journal of the Optical Society of America A, submitted to the Journal of the Optical Society of America A.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

8.1 Faculty Principal Investigators

a. Sources and Sensors

Robert W. Boyd, Professor of Optics
Dennis G. Hall, Professor of Optics
Stephen D. Jacobs, Scientist in The Institute of Optics and Senior Scientist in the Laboratory for Laser Energetics
Michael G. Raymer, Associate Professor of Optics
Carlos R. Stroud, Professor of Optics
Kenneth J. Teegarden, Professor of Optics

b. Signal Processing & Image Understanding

Nicholas George, Professor of Optics and Program Director
G. Michael Morris, Associate Professor of Optics
Emil Wolf, Professor of Physics and Astronomy and Professor of Optics

c. Optical Systems Design

Gregory W. Forbes, Assistant Professor of Optics
Duncan T. Moore, Director, The Institute of Optics
John R. Rogers, Assistant Professor of Optics

8.2 Degrees Awarded

"Contributions to the theory of the electronic and optical properties of Si-Ge_xSi_{1-x} semiconductor superlattices," C. Martijn de Sterke (Thesis advisor: Professor Dennis G. Hall), completed December, 1987.

DATE	LOCATION	CONTACT	UR FACULTY	SUBJECT
10/15/86	U.S. Army Armament R&D Center First Control Division Dover, NJ 07801	Lester, James	Jacobs, Stephen	Overview of UR OES program Optical material program
10/29-30/86	Air Force Weapons Lab Kirtland AFB, NM 87117	Wilson, LeRoy	Boyd, Robert	Workshop on nonlinear optical techniques for SDI applications
10/30/86	U.S. Army Missile Command Redstone Arsenal, AL	Hartman, Richard Christensen, Charles	Morris, G. Michael	Overview of UR OES program Bandpass filters in telescope-imaging systems Automatic target detection
10/31/86	Eglin Air Force Base Fort Walton Beach, FL	Snyder, Don	Moore, Duncan	UR OES Overview Gradient Index
11/25/86	Night Vision and Electro-Optics Center Fort Belvoir, VA	Garn, Lynn Shields, Frank	Morris, G. Michael	Image recognition at low light levels
2/11/87	Letterman Army Institute of Research Presidio of San Francisco, CA	Stuck, Bruce Beatrice, E.S. Lund, Jack	Jacobs, Stephen	Overview of optical materials research program

Section 9.1: Faculty Visits for Technology Transfer

DATE	LOCATION	CONTACT	UR FACULTY	SUBJECT
3/23-25/87	Army Research Office Geosciences Division Research Triangle Pk, NC	Flood, Walter A.	Wolf, Emil	Propagation in random media and scattering from rough surfaces
4/16/87	Night Vision and Electro-Optics Center Fort Belvoir, VA	Buser, Rudolf	Boyd, Robert Jacobs, Stephen	Overview of UR OES program and familiarization of Night Vision
6/4/87	Night Vision and Electro-Optics Center Fort Belvoir, VA	Buser, Rudolf	George, Nicholas Hall, Dennis Jacobs, Stephen Moore, Duncan Morris, G. Michael Raymer, Michael Rogers, John Stroud, Carlos	Overview of UR OES program and familiarization of Night Vision
6/17/87	Night Vision and Electro-Optics Center Fort Belvoir, VA	Daunt, Geraldine Chandra, Suresh Caffey, David	Kelly, John	Cr/Nd/GSGG
6/19/87	Harry Diamond Laboratories Adelphi, MD	Scully, John Berg, Norman	George, Nicholas Morris, G. Michael	Automatic pattern recognition
6/25&26/87	SAIC McLean, VA	Cronin, Robert	George, Nicholas	Survey of optical pattern recognition (no expense to UR/SAIC paid)

Section 9.1: Faculty Visits for Technology Transfer - Continued

DATE	LOCATION	CONTACT	UR FACULTY	SUBJECT
7/9/87	Night Vision and Electro-Optics Center Fort Belvoir, VA	Pollard, John Armirtharaj, Paul	Schmid, Ansgar	Materials characterization and instruments
10/23/87	Letterman Army Institute of Research Presidio of San Francisco, CA	Pohlmann, J. Stuck, Bruce	Jacobs, Stephen Marshall, Kenneth	Optical power limiters
11/20/87	Night Vision and Electro-Optics Center Fort Belvoir, VA	Buser, Rudolf Norton, Mark	Wolf, Emil	Red shifts of spectral lines Wavefront correction
12/2/87	U.S. Army Missile Command RedstoneArsenal, AL	Hartman, R.L. Johnson, John	Wolf, Emil	Red shifts of spectral lines

Section 9.1: Faculty Visits for Technology Transfer - Continued

DATE	U.S. ARMY PERSONNEL	LOCATION	UR CONTACT	SUBJECT
10/20/87	Chandra, Suresh	U.S. Army Center for Night Vision and Electro-Optics Fort Belvoir, VA 22060-5677	Jacobs, Stephen Schmid, Ansgar	Tour of repetition rate lab and OMEGA laser system
10/22/87	Durvasula, L.N.	U.S. Army Center for Night Vision and Electro-Optics Fort Belvoir, VA 22060-5677	Boyd, Robert	Coherence of scattered laser light
10/23/87	Durvasula, L.N.	U.S. Army Center for Night Vision and Electro-Optics Fort Belvoir, VA 22060-5677	George, Nicholas	Holograms for laser protection

Section 9.2: U.S. Army Personnel Visits for Technology Transfer

10. BRIEF OUTLINE OF RESEARCH FINDINGS

*Sabbatical Leave, AY 1987-88.

SOURCES & SENSORS

NONLINEAR OPTICS

Robert W. Boyd

Our work over the past year has included studies of optical phase conjugation, four-wave mixing, and the stability characteristics of nonlinear optical processes. We have been interested both in studying optical phase conjugation as a means of optical processing and in studying processes that compete with the four-wave mixing interaction and hence can limit the performance of phase conjugate mirrors.

We have performed an experimental study of the relative phase between the field incident upon and the field generated by a phase conjugate mirror. We are interested in this problem because some phase conjugate mirrors impart a random overall phase to the generated wave. To examine this question, we have studied the nature of the fringe pattern produced by interference between a wave incident upon a phase-conjugate mirror and that leaving the mirror. The fringe locations are found to depend on the phase of the wave incident upon the mirror, in agreement with recent theoretical predictions but in contrast to the results observed for the interference pattern produced on reflection at an ordinary metal mirror. The phases of the waves that pump the phase-conjugate mirror provide the reference with respect to which the phase of the incident wave is determined.

There has recently been considerable interest in nonlinear optical interactions in which two different processes compete with one another. For example, we have studied how the process of amplified spontaneous emission can compete with the four-wave mixing process. In our experimental investigation of this competition, we have found that under two-photon excitation of the sodium 3d level, new optical frequency components can be generated either by amplified spontaneous emission at the 3d → 3p transition frequency or by a resonantly enhanced four-wave mixing process. We have observed competition between these two processes, resulting in the suppression of amplified spontaneous emission. The transfer of population to the 3d level is inhibited by the destructive interference between two different pathways connecting the ground and upper levels.

We have also worked on the stability characteristics of nonlinear optical processes. We have shown the counterpropagating pump waves (for instance, of the sort used to pump a phase conjugate mirror) can give rise to instabilities and chaos. In detail, we have shown that the polarizations of counterpropagating light waves in an isotropic Kerr medium are temporally unstable when their total intensity exceed a certain threshold value. Periodic and chaotic temporal behavior can occur in the output polarizations and under certain conditions also in the output intensities. An experiment to confirm these theoretical predictions is now in progress. We have also performed a theoretical study of how noise affects the four-wave mixing process.

SILICON-BASED INTEGRATED OPTICS

Dennis G. Hall

This research attempts to identify and demonstrate physical mechanisms and structures that will make it possible to define an optoelectronics technology based in silicon. It is likely that silicon will continue to be the primary material of choice for the microelectronics industry for a very long time. There is, therefore, a very real opportunity to expand the capabilities of the present-day microelectronics industry by combining optical and electronics technologies in/on silicon.

We have made encouraging progress during the last year in two main areas: 1) mechanisms for obtaining near-infrared optical emission from silicon, and 2) silicon-compatible optical waveguide structures. Each is described below in a short paragraph.

Our investigations of the radiative decay of excitons bound to isoelectronic impurities in crystalline silicon currently focus on chalcogen impurities (sulfur, selenium, and oxygen). We reported, in 1986, our discovery of a sulfur-related impurity complex that gives rise to unusually strong emission near the wavelength $\lambda = 1.32\ \mu m$ at temperatures at and above the temperature of liquid nitrogen (77K), but below room temperature.[1] Subsequent experiments revealed that the emission most likely originates with the radiative decay of an exciton bound to a sulfur-oxygen isoelectronic complex.[2] We have now shown that very similar results occur in the case of selenium-doped silicon (Se is directly below S on the periodic table), and it appears that the emission originates with the radiative decay of an exciton bound to an isoelectronic selenium-oxygen complex.[3] Perhaps our most exciting and newest discovery is the observation of room-temperature emission near the wavelength $\lambda = 1.6\ \mu m$ from oxygen-doped silicon. The specific nature of this emission and the impurity complex from which it originates is the subject of our current investigations.

Our investigations of silicon-compatible optical waveguides for use in the near-infrared region of the spectrum have also led to several interesting results. We successfully demonstrated the excitation of waveguide modes in an epitaxial silicon waveguide by the radiative decay of excitons bound to impurities

1 T.G. Brown and D.G. Hall, "Optical emission at 1.32 μm from sulfur-doped crystalline silicon," Appl. Phys. Lett. **49**, 245 (1986).

2 T.G. Brown, P.L. Bradfield, and D.G. Hall, "Concentration dependence of optical emission from sulfur-doped crystalline silicon," Appl. Phys. Lett. **51**, 1585 (1987).

3 P.L. Bradfield, T.G. Brown, and D.G. Hall, "Radiative decay of excitons bound to chalcogen-related isoelectronic impurity complexes in silicon," submitted to Physical Review Letters, January, 1988.

4 T.G. Brown, P.L. Bradfield, D.G. Hall, and R.A. Soref, "Optical emission from impurities within an epitaxial-silicon optical waveguide," Opt. Lett. **12**, 753 (1987).

5 B.N. Kurdi and D.G. Hall, "Optical waveguides in oxygen-implanted buried-oxide silicon-on-insulator structures," accepted for publication in Optics Letters, February, 1988.

introduced into the waveguide by ion-implantation.[4] This demonstration is significant because it shows the ease with which standard processing techniques can be used to create an optoelectronic device in silicon. We also showed, theoretically, that a silicon-on-insulator structure currently being developed for the microelectronics industry, is capable of functioning as a low-loss optical waveguide.[5] We are in the midst of an experimental investigation, and have just observed the propagation of optical guided-waves in this silicon-on-insulator structure for the first time.

LIQUID CRYSTAL OPTICS FOR LASERS

Stephen D. Jacobs

1. Liquid Crystal Metal Complexes (K. Marshall and S. Jacobs)

We have synthesized a nematic liquid crystalline organometallic complex, bis (p-n-butylstyryl-1,2-dithiolato) nickel, which possesses an extremely strong absorption maximum near 850 nm and displays a strong dichroism of the absorption band when dissolved in a conventional nematic liquid crystal host. The new material has demonstrated a solubility in nematic liquid crystal materials as high as 10% w/w., nearly 5 - 10 times higher than that of the conventional nonmesogenic dyes commonly reported in the literature. The high solubility of the liquid crystal dye in nematic host materials and the broad absorption band of the resulting mixture allows blocking extinctions of OD = 3 at 1 µm to be obtained for a 100 µm path length of material at a 10% dye concentration; for 850 nm radiation, the same blocking extinction can be achieved with 24 µm path length of material and a 1% dye concentration. The dichroic nature of the metal complex allows the blocking or modulation of near infrared laser sources (e.g., diode, YAG) by external electric field-induced reorientation of the host liquid crystal molecules. Optical field-induced switching with these materials is also of interest and will be the subject of future investigations.

2. Chiral Smectic C Mesogens (K. Marshall, A. Schmid, and S. Jacobs)

A synthesis method has been developed and tested for the preparation of stilbene and tolane liquid crystal compounds possessing the ferroelectric chiral smectic C phase. These materials are anticipated to have interesting nonlinear optical properties due to the noncentrosymmetric nature of the chiral smectic C phase and the extensive electron delocalization in the molecules, as evidenced by the high birefringence of their nematic analog (0.3). Both stilbene and tolane derivatives containing a decyloxy and nonchiral n-hexyl terminal group were successfully synthesized and characterized as a preliminary test of the validity of the synthesis method. The liquid crystal textures of the products were identified as smectic A (stilbene) and smectic B (tolane) by hot-stage polarizing microscopy. Replacement of the n-hexyl terminal group with an alkyl group containing an asymmetric center and the introduction of a lateral dipole into the molecule is expected to produce the chiral smectic C phase in these materials. Synthesis efforts to introduce the assymetric 2-methylbutyl group into the molecule are currently underway.

3. Chiral Smectic A Mesogens (K. Marshall, A. Schmid, and S. Jacobs)

We have expanded our research efforts in the synthesis and characterization of nonlinear optical properties of liquid crystal materials to include mesogens containing the chiral smectic A phase. Like the chiral smectic C materials, these compounds are noncentrosymmectric and can possess a large birefringence; in fact, many chiral smectic C mesogens exhibit the chiral smectic A phase at elevated temperature. Since the director orientation in the chiral smectic A phase is normal to the layer planes, it is possible to align these materials with the layer planes parallel to a pair of confining substrates so that an optically transparent film can be produced. The interaction of a laser beam with this highly ordered smectic structure produces a molecular reorientation caused by coupling of the molecular polarizability with the polarized incident radiation. The result of this molecular reorientation is scattering of the incident laser radiation. Such a laser-induced light scattering effect could be useful as an optical power limiting technique and will be the subject of our future investigations.

Since materials possessing the chiral smectic A phase at room temperature are currently unavailable, our synthesis efforts shall focus on producing materials with a room temperature chiral smectic A phase and a large molecular polarizability. The latter property is especially desirable in order to produce materials with large opto-optical effects and fast response. A series of compounds consisting of substituted napyhalenes joined to an alky-or alkoxy-substituted phenyl group by connecting linkages such as ester, stilbene, tolane, carbodiimide, propyne ($-C \equiv C-CH_2$), thioether $-(H_2C-S-CH_2)-$, and azine $-(HC=N-N=CH-)$ are currently being prepared and will be evaluated for their nonlinear optical response in the future.

4. **Chemical Modification of Polyacrylates and Polymethacrylates** (S. H. Chen, K. Marshall, and Y. Maa)

During the present reporting period, it was determined that Keller's method for the preparation of liquid crystalline polymers under liquid-liquid phase transfer conditions has, in fact, resulted in another low molar mass liquid crystal via ester hydrolysis of the starting liquid crystal mesogens. A mechanism was proposed for the unexpected reaction and was substantiated with independent reaction schemes. The results were summarized in a manuscript, which has been accepted for publication by Macromolecules. Alternative methodologies, including reaction in polar aprotic solvents and reaction via tetrabutylammonium polyacrylate and polymethacrylate, were also tested to enhance the conversion to liquid crystal polymers. It was found that by using tetrabutylammonium salt, instead of sodium salt, the yield of liquid crystal polymers could be increased from 10% up to 70%, a discovery of practical significance. The results for chemical modification in hexamethylphosphoramide were summarized in a manuscript submitted to Macromolecules for publication. It appears that we have arrived at an optimal set of conditions for the preparation of liquid crystal polymers based on chemical modification. We are currently finishing up additional experiments for the preparation of a manuscript to cover the extensive results obtained in recent months.

5. **Selective Reflection Liquid Crystal Polymers** (S. H. Chen, K. Marshall, and M. Tsai)

A series of selective reflection liquid crystal copolymers based on cholesterol and cholestanol was synthesized and characterized. We made the following observations: (1) the selective reflection wavelength is a function of the comonomer ratio; (2) the selective reflection wavelength can also be tuned with the composition of a mixture of two copolymers; (3) the molecular alignment can be enhanced by annealing at temperatures close to but below the cholesteric to isotropic transition; (4) the copolymers are reasonably stable upon prolonged heating at temperatures up to 250°C; and, (5) the laser damage resistance is acceptable for most applications. The results were presented in both 17th Northeast Regional ACS Meeting and in AICLE 1987 Annual Meeting. The copolymers based on cholesterol and cholestanol as presented above were found to be left-handed. In an effort to identify and synthesize right-handed polymers, we are currently working on other copolymers and a series of chemically modified hydroxypropylcellulose. It is hoped that an understanding of how to formulate right-handed polymers can be developed from studies of several sample systems. No theory for predicting handedness in cholesteric liquid crystalline polymers exists.

COHERENCE PROPERTIES OF NONLINEAR OPTICAL PROCESSES

Michael G. Raymer

A new type of intense light, called "amplitude-stabilized chaotic light," has been generated. This is light with no amplitude fluctuations, but having rapid, random fluctuations of phase. The statistics of the phase fluctuations are the same as those in thermal, or blackbody radiation (known also as chaotic light). This light was generated by passing amplified spontaneous emission from a Nd:YAG laser-pumped dye cell through a series of saturated dye amplifiers. It was found that the phase modulation of the light is not altered during the smoothing process.

The "amplitude-stabilized chaotic light," with wavelength 560 nm, was used as the pump in a H_2 Raman generator to produce Stokes-shifted light at 740 nm. This Stokes light has phase fluctuations that are nearly perfectly correlated to those of the pump light. When these two correlated beams were then used to study coherent anti-Stokes Raman scattering (CARS) in a second H_2 cell, a dramatic effect was observed. Depending on the detuning from Raman resonance (controlled by varying the H_2 pressures), the CARS signal was either enhanced (zero detuning) or suppressed (large detuning), compared to the case of no correlation between the two beams. More detailed studies are now underway to understand this behavior.

LASER SYSTEMS: INSTABILITIES AND DYNAMICS/SOURCES AND SENSORS

Carlos Stroud

The work in this area has progressed well during the past contract period, with two experimental projects and two theoretical projects completed. The first experimental project is the observation of a series of resonances at subharmonics of the Rabi frequency in a homogeneously broadened absorber. The subharmonic resonances have been suggested as the cause of a series of instabilities that have been observed in cw dye lasers. This experiment was the first observation of this structure produced by a 100% amplitude modulated beam driving a strongly saturated transition. In a related experiment it was observed that when a homogeneously broadened laser is pumped by a laser which is itself amplitude modulated simultaneously at two frequencies, the behavior of the optically pumped laser is quite different depending on whether the two modulation frequencies are rational or irrational multiples. In the case of rational multiples the spectrum of the laser contains series of combination tones of the two modulation frequencies. In the case of irrational multiplies, the laser output is chaotic, and the corresponding rf spectrum is broadband.

In another series of studies of the dynamics of micromasers some interesting results have been obtained. A theoretical study was carried out of the way in which an absorber that is turned on in a time short compared to the cavity round trip time effects the fields in a cavity. It was found that the effect is well described by a "darkness wave packet" that is emitted by the absorber and propagates out in the cavity, reflecting off of the walls and returning to modify the dynamics of the absorber. The applications of this analysis to intracavity Raman conversion are presently being studied.

SIGNAL PROCESSING & IMAGE UNDERSTANDING

OPTO-ELECTRONIC SYSTEMS

Nicholas George

An analysis was completed of the diffraction pattern in the shadow of a circular disc. This is compared to the on-axis diffraction behind a conducting sphere and a square aperture.

For automatic recognition systems that have correlation type of pre-processing, we have discovered a novel correlator configuration that will work well with 3-D objects illuminated in white light. This system consists of a cascade of a spatial sine transform, a real valued filter in the transform plane, and a spatial cosine transform. At present we have completed the basic theoretical treatment showing that such a system is feasible. The particular advantage of this system is that it produces a desirable narrow-spike indicating correlation (yes) and a quiet level background when there is no correlation. Computer simulations have been used to verify the theory. During the next period, we will assemble the actual correlator hardware.

In building this system we have need for a variable phase shifter that provides precisely the same phase shift for all wavelengths. During this period, we discovered a simple holography system with three gratings (periods Λ, $\Lambda/2$, Λ) that will provide this phase shift. Experiments were conducted to prove the concept and a paper has been published on this subject, i.e., the achromatic phase-shifter.

OPTICAL PROCESSING AND STATISTICAL OPTICS

G. Michael Morris

1. Quantum-Limited Imaging and Image Processing

a. Image Classification

Our research on image classification involves the development of correlation filters that can be used to automatically discriminate classes, or categories, of images. Approaches to the problem have traditionally relied on synthesis of a filter that seeks to maximize the separability of correlation output for different classes or that attempts to specify the output through a direct mapping. In these approaches, rudimentary decision theory is applied to the correlation output to complete the classification procedure. The approach currently under consideration is to use statistical decision theory from the outset to form an optimum filter for image classification. In this manner, the well-known maximum-likelihood decision strategy, and the related probability-of-error and Bayes risk strategies, can be directly applied to the problem.

The filter for maximum-likelihood image classification was originally derived with a view toward implementation in a low-light-level (photon-limited) image correlation system. Hence, the original derivation contained an assumption that the number of photons contained in the output image was very small. Recently, a new formulation has revealed that under certain assumptions about the image classes, the low-photon count assumption is unnecessary. As a result, the door has been opened to investigation of the maximum-likelihood filter as a new tool for use in optical correlators and other standard correlation schemes. Research in this direction is currently under way.

The maximum-likelihood impulse response function is bipolar in nature, taking on both positive and negative values. As with other filters of this type, problems in locating target objects can arise. Recently, a promising approach has been found in which the relevant information can be encoded into two non-negative functions, thus eliminating such problems. In the modified approach, only one additional filter is needed to accomplish a K-class sorting task (K, rather that [K-1]).

The work described above has been accepted for presentation at the SPIE meeting in Orlando, Florida, April 1988.

In the next contract period, the primary findings of recent months will be tested. First, the applicability of the maximum-likelihood filter to optical correlator implementation will be examined. Second, the shift-invariance of the optical correlator will be exploited to investigate the properties of the new two-filter format and its ability to provide accurate target location.

b. Dead-Time Effects in Photon Counters

Dead-time effects in single-channel and multiple-channel counters are being investigated in the context of photon counting related to imaging photodetectors. The imaging photodetector has one or more microchannel plates that amplify photoevents to produce detectable charge packets. Dead-time effects can be important when the imaging photodetector operates at high count rates. The research consists of two parts: fundamental aspects of the dead-time effect and its application to the generation of "non-classical" light, and an investigation of the local dead-time effects in a microchannel plate, which are due to the finite recovery time of an individual microchannel.

With regard to the generation of "non-classical" light, optical dead-time effects were considered both in theory and experiment. A paper on this work has been accepted for publication.

In the second part of the research, the dead-time effects of a pixel, which consists of a group of microchannels, is considered. Theoretical aspects of the problem were investigated in the context of a single- and a multiple-channel counter. An experimental investigation is also underway. In the experiments an imaging photodetector assembly has been assembled in a vacuum chamber. Instead of using a photocathode, ultraviolet light produced by the second-harmonic generation from a nonlinear crystal is used to excite the microchannel plate directly. A data-acquisition system was constructed using an IBM PC-AT microcomputer. We plan to investigate local dead-time effects in a variety of detector configurations: a single-channel electron multiplier, a single curved-channel microchannel plate, a "Chevron" configuration and a "V-Z" 5-plate system. We expect to begin data collection and analysis in this next contract period.

Also, we have modeled theoretically the effects of dead time in linear filtering for image recognition. Under suitable conditions we have found a simple expression for the probability density of the photodetection at the specified spatial position when local dead-time effects are included. This result can be used to correct for local dead-time effects when the imaging photodetector is operated at a high count rate. We are planning to test the theoretical predictions in the laboratory using the detection and vacuum system described above.

2. Optical Coherence: Theory and Experiments

The coherence properties of the light emanating from the source can have a profound influence on the outcome of optical experiments. For example, the statistical fluctuations of the light at the source play a central role in determining the character of the light distribution in the image plane of an optical system. Fluctuations of the index of refraction during propagation in a material also influence measurements of source information. It is therefore essential to know the coherence properties of the source in addition to those describing propagation and detection.

The statistical properties of the light emitted by a partially coherent source can modify the spectrum of light detected at a distant point. We have performed experiments that illustrate the influence of source correlations on the spectrum of light. These experiments provide further evidence that underscore the importance of knowing the statistical fluctuations at the source.

In this contract period, a presentation was given at the Optical Society meeting in Rochester in October 1987, and two manuscripts on the role of coherence in optical systems were accepted for publication.

3. Optical Applications of Neural Networks

In this contract period our research efforts have been directed toward an investigation of neural network architectures for pattern recognition. Computer simulations were performed that show the utility of a multilevel, feed-forward configuration, which is programmed (taught) using a program of supervised learning. In this method, members of a training set are presented to the network; the actual output of the network and the desired output are used to generate an error signal that is used to calculate the changes in the interconnection strengths between neurons. The amount of change for a particular connection is calculated by taking the derivative of the energy of the network with respect to that connection and performing a gradient descent, which uses that result to minimize the energy (energy is defined as the total squared error of the network output). Alternative definitions for the network energy are presently under consideration, as are new rules for the connection strength dynamics.

The type of work described above has its roots in early work on artificial intelligence. A comparative study is currently in preparation that compares and contrasts conventional pattern recognition schemes with more recent efforts involving neural networks. Our goal is to show how the conventional optical pattern recognition methods may be described in the context of neural networks and vice versa. For example, certain interconnection levels in neural network can be considered as classification filters. We have used a computer program to simulate a neural network. The interconnection strengths (filters) that were synthesized are very similar to those employed in the least-squares linear mapping technique reported by S. Lee and co-workers at UCSD.

We are investigating a three-level, neural-net architecture, which has shown promise for the problem of multi-class pattern recognition. In an optical implementation, this translates into fewer classification filters. It appears that it is possible to sort N classes using only $\log_2 N$ filters. We have successfully demonstrated this reduction for the case when there are $N = 4$ classes.

Plans to build optical implementations of neural network architectures are in progress. Two microchannel spatial light modulators have recently been acquired. These units possess many features important for a pattern recognition system of the type envisioned, including: image addition and subtraction, incoherent-to-coherent conversion, thresholding, and amplification. A thermoplastic holography system has also been received. The holography system is very flexible and is slated for use in the storage of synthesized classification filters. We plan to begin laboratory experiments involving neural-net architectures in the near future.

EFFECTS OF SOURCE COHERENCE ON RADIATED FIELDS

Emil Wolf

Most of the research was concerned with the influence of the coherence properties of a source on the nature of the radiation field that the source generates. In particular, new results were obtained regarding the dependence of power radiated by certain sources on their degree of coherence.

We have also been investigating the effect of source coherence on the spectrum of the emitted light, and we studied how the spectrum of the light may differ from that of the source fluctuations. The results have potential applications in connection with signal modulation as they suggest that one might be able to modify radiation spectra by controlling source coherence.

OPTICAL SYSTEMS DESIGN

OPTICAL SYSTEM DESIGN

Gregory Forbes

The project has two main components related to the optimization phase of optical system design. Typically, optimization is by far the most computationally demanding stage in the design process and is dominated by the work done in assessing the myriad systems proposed during this phase.

An investigation of the efficiency of a variety of means of assessing the performance of a proposed optical system is being carried out as part of the first component of the project. The first paper to come out of this work (submitted to *Journal of the Optical Society of America A*) concerns the efficiency of assessment schemes based on numerical ray tracing and contains some striking results. It is shown that by using appropriate variables to parameterize the rays, taking advantage of system symmetries and adopting the method of Gaussian quadrature, it is possible to increase the efficiency of determining a figure of merit by orders of magnitude. The methods developed during this first stage of the research may well be hard to better. However, one of the main goals of this component is to consider the use of aberration series as an alternative to numerical ray tracing and this work is presently being completed.

The second component of the project involves the investigation and applications of global optimization routines. In particular, simulation of the "simulated annealing algorithm" is being carried out in an attempt to uncover empirically optimal annealing schedules and the random step generation rules. This work is still in a relatively early stage although, from recent indications, it seems that some interesting results may be on the horizon.

GRADIENT INDEX OPTICS

Duncan T. Moore

Since the last report, progress has been made in several experimental areas. The first of these is Czochralski growth of fluoride crystals for use in the UV portion of the spectrum. A new type of crucible has been used with very satisfactory results. Graphite was used as a crucible material but graphite dust floating in and on the melt impeded growth of good crystals. Pure vitreous carbon crucibles, which have the same inert properties as graphite, with respect to fluoride compounds, were tried with excellent results. Unfortunately, their coefficient of thermal expansion is close to that of glass, and the crucibles were unable to take the thermal cycling in the growth chamber without shattering after several runs. The crucible currently in use is a graphite crucible, coated on the inside with a thin layer of vitreous carbon. This eliminates the dust problem and is thermally robust. (At a price half that of the pure vitreous carbon crucible with three to four times the life span. Industry often uses platinum.)

Using the new crucibles, the region over which BaF_2 and CaF_2 are soluble and transparent when pulled from the melt was investigated. This range appears to be approximately zero to five percent CaF_2 . Further growth is necessary to determine if this range can be extended. Currently, methods for introducing CaF_2 into the melt during growth on a dynamic basis are being explored. Several other fluoride materials were melted, and in the case of barium/lithium fluoride, crystals were grown. Although their phase diagram indicates solubility of lithium fluoride in barium fluoride with a segregation coefficient of two, no gradient was visible in grown crystals due to local inhomogeneities.

The second area in which progress has been made is in metrology. The main optical components of the moire deflectometer (to be used in testing the crystals) have been assembled, along with the electronics and the interface to an IBM PC-AT. Phase noise measurements have been made, and are on the order of P 100. (P is the grating period, in this case, twenty-five microns.) The noise appears to be independent of the spacing of the gratings and implies a precision approaching that of optical interferometers. Further work needs to be done to calibrate the deflectometer and to investigate the use of an incoherent source.

In theoretical areas, research has begun on optimization algorithms. Nearly all of the currently available optimization algorithms in optical lens design require constant human intervention. The final design often depends on the lens designer's prior knowledge and experience. A new approach using simulating annealing to lens design is being investigated. Simulated annealing is a stochastic approach to the solution of a complex system and is a form of Monte Carlo methods. It is a search algorithm driven by a biased random walk. As applied to lens design, a given lens system's performance can be characterized in terms of its merit function. The merit function is reduced when the lens system attains better image quality. The objective is to find the lowest merit function for a given lens system where its image quality is maximized. Because the merit function contains numerous local minima, nearly all of the currently available optimization methods get trapped in local minima and fail to locate the best possible solution unless specific expert knowledge from the lens designer is available to the program. By the construction of its merit function, simulated annealing can not be trapped in local minima; thus, it is capable of locating the very best solution.

Basic research on the nature of simulated annealing has been conducted during the past six months. To facilitate the investigations, a computer program using aforementioned method which optimizes an n-dimensional function has been completed. A computer lens design program using aforementioned method for spherical surfaces based on paraxial and third order theory has been completed. The preliminary results from both computer programs are favorable. Currently, the lens design program is being upgraded to include all orders of calculations or real ray analysis, with additional features being added.

This new approach to lens design can reduce the need for human expertise and is capable of locating the best overall solution for a given lens system. Further research on the possibility of reducing this method's computational requirements will be examined in the near future.

EVAPORATIVE DEPOSITION OF ASPHERIC SURFACES

John R. Rogers

The objective of this research is to investigate the use of evaporative deposition for the production of aspheric surfaces, possibly to include certain classes of surfaces without rotational symmetry.

An initial investigation was made of the surface roughness properties of thick (up to approximately six microns) deposits of silicon dioxide (SiO_2) and Tantalum Pentoxide (Ta_2O_5) on float glass substrates. The surface roughness was measured with a Talystep stylus profilometer, and found to be about 35 Angstroms rms for both SiO_2 and Ta_2O_5. Because the rate of deposition was much more controllable, it was decided to concentrate on the use of Ta_2O_5.

A monte-carlo simulation of the fabrication process was written, and it was found that the sensitivity of the process to decentrations of the source and the mask were substantially reduced by incorporating four-fold symmetry into the mask.

The fabrication technique was found to work well when the mask was nearly in contact with the substrate. An asphere introducing 8 visible wavelengths of spherical aberration at best-focus (similar to a Schmidt corrector plate) was deposited onto a flat substrate using a mask corrected to account for the measured angular distribution of the source. The resulting asphere was correct to one-tenth wavelength at $\lambda = .6328\ \mu$.

Preliminary simulations indicated that a type of aspheric surface useful for tilted-component optical systems could be fabricated by deposition onto a tilted substrate. For a 45 degree tilt angle and a substrate diameter of 100 mm, this requires a mask-to-substrate distance of approximately 75 mm, and the resulting blurring effect of the mask causes significant smoothing of the features of the asphere. To correct for this, a mask optimization program was written, incorporating the source distribution into the monte-carlo simulation. The spatial distribution of the source was calculated by measuring the deposited thickness function for a step-function mask (analogous to the optical "edge-response function"), differentiating to obtain the "line spread function", and inverse Abel transforming to obtain the "point spread function", which was then scaled to the coordinates of the source plane.

A significant and somewhat surprising discovery was that in order to correct the mask to account for the blurring, the deposit thickness inside the region of interest must be biased significantly thicker, in order that the deposition function outside the region of interest may taper smoothly to zero.

11. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

11.1 Sources and Sensors

"Interference pattern produced on reflection at a phase conjugate mirror. Part I. Theory," E. Wolf, L. Mandel, R.W. Boyd, T.M. Habashy, and M. Nieto-Vesperinas, J. Opt. Soc. Am. B **4**, 1260-1265 (1987).

"Interference pattern produced on reflection at a phase conjugate mirror. Part II. Experiment," Arturo A. Jacobs, Wayne R. Tompkin, Robert W. Boyd, and Emil Wolf, J. Opt. Soc. Am. B **4**, 1266-1268 (1987).

"Instabilities and chaos in the polarizations of counterpropagating light fields," Alexander L. Gaeta, Robert W. Boyd, Jay R. Ackerhalt, and Peter W. Milonni, Phys. Rev. Lett. **58**, 2432-2435 (1987).

"Optical emission from impurities within an epitaxial-silicon optical waveguide," T.G. Brown, P.L. Bradfield, D.G. Hall, and R.A. Soref, Opt. Lett. **12**, 753-755 (1987).

"Optical waveguides in oxygen-implanted buried-oxide silicon-on-insulator structures," B.N. Kurdi and D.G. Hall, Appl. Phys. Letters **51(Feb)**, xxx-yyy (1988).

"Competition between four-wave mixing and amplified spontaneous emission," M.S. Malcuit, D.J. Gauthier, and R.W. Boyd, in **Hyperfine Interactions**, J.C. Baltzer A.G. Scientific Publishing Company, pp. xxx-yyy (1988).

"Quantum theory of Rabi sideband generation by forward four-wave mixing,' G.S. Agarwal and R.W. Boyd, submitted to Physical Review A.

"Laser instabilities," C.R. Stroud, Jr., to be published in Proceedings of the Twelfth International Nathiagali Summer College on Physics and Contemporary Needs, Nathiagali, Pakistan, 18 June - 9 July 1987.

"Transients in the micromaser," C.R. Stroud, Jr., to be published in Proceedings of the Twelfth International Nathiagali Summer College on Physics and Contemporary Needs, Nathiagali, Pakistan, 18 June - 9 July 1987.

"Near-infrared dichroism of a mesogenic transition metal complex and its solubility in nematic hosts," K.L. Marshall and S.D. Jacobs, accepted for publication in Molecular Crystals and Liquid Crystals.

"A reexamination of the synthesis of liquid crystalline side-chain polyacrylates via liquid-liquid phase transfer catalysis," S.H. Chen and Y.F. Maa (S. Jacobs), accepted by Macromolecules.

"The preparation of liquid-crystalline side-chain polyacrylate by chemically modifying poly (sodium acrylate) in hexamethylphosphoramide," S.H. Chen and Y.F. Maa (S. Jacobs), submitted to Macromolecules.

"Above-threshold ionization with femtosecond pulses: a comparison of quantum and classical predictions," Jonathan Parker and C. R. Stroud, Jr., submitted to Physical Review Letters.

"Transient absorption by a Rydbrg atom in a resonant cavity," Mark Mallalieu, Jonathan Parker, and C. R. Stroud, Jr., submitted to Physical Review A.

"Amplitude-stabilized chaotic light," C. Radzewicz, Z. W. Li, and M. G. Raymer, submitted to Physical Review A.

11.2 Signal Processing & Image Understanding

"Sine-cosine cascade correlator with real-valued filters," Shen-ge Wang and Nicholas George. Opt. Lett. **12**, 383-385 (1987).

"Diffraction from a circular aperture: on-axis field strength. R. Edward English, Jr. and Nicholas George. Appl. Opt. **26**, 2360-2363 (1987).

"The instantaneous cross-spectral density of non-stationary wavefields," Brian Cairns and Emil Wolf, Opt. Comm. **62**, 215-218 (1987).

"Spectral shifts produced by source correlations," Dean Faklis and G.M. Morris, Opt. Lett. **13**, 4-6 (1988).

"Spectral modulation by control of source correlations," Avshalom Gamliel and Emil Wolf, Opt. Comm. **65**, 91-96 (1988).

"White light interferometry with an achromatic phase shifter," Nicholas George and Thomas Stone, submitted to Proc. Soc. Photo-Opt. Instr. Eng. **883**, xxx-yyy (1988).

"Diffuser radiation patterns over a large dynamic range," Lyle G. Shirley and Nicholas George, accepted for publication in Applied Optics.

"Diffraction patterns in the shadows of disks and obstacles," R. Edward English, Jr. and Nicholas George, submitted to Applied Optics.

"Generation and statistical properties of optical dead-time effects," Doo Jin Cho and G. Michael Morris, submitted to the Journal of Modern Optics.

"Pattern recognition using photon-limited images," G. Michael Morris. Chapter in a book on **Optical Computing and Processing**. To be published by Academic Press. Henri Arsenault and Tomasz Szoplik are editors.

"Changes in the spectrum of partially coherent light beam propagating in free space," Zagorka Dacic and Emil Wolf, submitted to the Journal of the Optical Society of America A.

11.3 Optical Systems Design

"Radial gradient-index eyepiece design," John P. Bowen, J. Brian Caldwell, Leo R. Gardner, Niels Haun, Michael T. Houk, Douglas S. Kindred, Duncan T. Moore, Masataka Shiba, and David Y.H. Wang, submitted to Applied Optics.

"Optical System Assessment. I," G. W. Forbes, submitted to the Journal of the Optical Society of America A, submitted to the Journal of the Optical Society of America A.

SOURCES & SENSORS

Reprinted from Journal of the Optical Society of America B, Vol. 4, page 1260, August 1987

Interference pattern produced on reflection at a phase-conjugate mirror. I: Theory

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Received July 7, 1986; accepted April 15, 1987

The structure of the fringe pattern that results from the interference between a plane monochromatic wave of any state of polarization incident upon a phase-conjugate mirror and the wave reflected from the mirror is analyzed theoretically. It is found that the locations of the fringe maxima and minima depend on the phase of the incident wave, in contrast to the situation involving an ordinary metal mirror. Some of the results are applied to situations that represent the "phase-conjugate analogs" of classic experiments of O. Wiener on standing waves of light. A comparison is made between his results and those that would be obtained in experiments involving a phase-conjugate mirror in place of an ordinary metallic mirror.

1. INTRODUCTION

In classic experiments carried out toward the end of the last century Wiener[1] demonstrated the existence of standing waves of light and also showed that the photochemical action responsible for the blackening of a photographic plate is directly related to the electric rather than to the magnetic field vector. These experiments involved measurements of the positions of fringes formed by interference between a plane electromagnetic wave incident upon a highly reflecting plane mirror and the wave reflected from the mirror.

In the present paper we investigate theoretically the structure of the interference pattern that is formed when a plane electromagnetic wave is incident upon a phase-conjugate mirror rather than upon an ordinary mirror. We then specialize the results to situations that are analogous to those pertaining to Wiener's experiments.

In Section 2 we derive general expressions for the distribution of the time-averaged electric energy density in the interference pattern formed when a plane electromagnetic wave of any state of polarization and any direction of incidence falls upon a phase-conjugate mirror. The phase-conjugate mirror is of arbitrary reflectivity and is assumed to produce a complete reversal of the state of polarization of the incident wave.

In Section 3 we analyze the structure of the pattern. We find, in particular, that unlike in the situation involving an ordinary mirror, the locations of the intensity maxima and minima depend on the phase of the incident wave.[4,5]

In Section 4 we specialize the results to the situation when the absolute value of the reflectivity of the phase-conjugate mirror is unity. This is the situation that, with certain directions of incidence, is the "phase-conjugate analog" of Wiener's experiments. With an ordinary highly reflecting mirror a standing wave is formed only when a plane wave is incident upon it along the normal to the mirror surface. In contrast to this situation we find that with a phase-conjugate mirror a standing wave is formed irrespective of the angle of incidence.

Some of our results can be understood from qualitative considerations based on the well-known action of a phase-conjugate mirror in reflecting the incident wave back upon itself. For this reason the form of the interference pattern does not depend on the angle of incidence. Other results are, however, intuitively less obvious, and their derivation needs a more detailed mathematical analysis such as is presented in this paper. Examples are the dependence of the fringe visibility on the reflectivity of the phase-conjugate mirror and on the state of polarization of the incident field.

Some of our predictions have been recently confirmed by experiment.[6,7]

2. DISTRIBUTION OF THE TIME-AVERAGED ELECTRIC ENERGY DENSITY PRODUCED BY REFLECTION OF A PLANE WAVE AT A PHASE-CONJUGATE MIRROR

Let[8]

$$\mathbf{E}^{(i)}(\mathbf{r}, t) = \epsilon A^{(i)} \exp[i(\mathbf{k}_i \cdot \mathbf{r} - \omega t)] \tag{2.1}$$

Reprinted from Journal of the Optical Society of America B, Vol. 4, page 1266, August 1987

Interference pattern produced on reflection at a phase-conjugate mirror. II: Experiment

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Received July 7, 1986; accepted April 15, 1987

The nature of the fringe pattern produced by interference between a wave incident upon a phase-conjugate mirror and that leaving the mirror has been studied experimentally for a phase-conjugate mirror based on degenerate four-wave mixing. The fringe locations are found to depend on the phase of the wave incident upon the mirror, in agreement with recent theoretical predictions but in contrast to the results observed for the interference pattern produced on reflection at an ordinary metal mirror. The phases of the waves that pump the phase-conjugate mirror are shown to provide the reference with respect to which the phase of the incident wave is determined.

A recent theoretical analysis[1] of the interference pattern produced on reflection at a phase-conjugate mirror (PCM) has shown that the positions of the interference fringes thereby produced depend on the phase of the incident wave. This predicted behavior is in contrast to that observed in the classic experiments of Wiener[2] for reflection at the surface of a metal mirror, in which case the resulting interference pattern has a node at the surface of the mirror, regardless of the phase of the incident field. In this paper we present experimental results that demonstrate the nature of the fringe pattern produced by interference between the wave incident upon the PCM and that reflected from it for the case of a PCM that operates by means of degenerate four-wave mixing (DFWM). These results are in good agreement with the theoretical predictions of Ref. 1 and also indicate that the phases of the waves that pump the PCM provide a reference with respect to which the phase of the incident wave becomes evident in the resulting interference pattern.

In the usual geometry of DFWM, the incident signal field and the forward-going pump wave both enter the nonlinear medium through the same face, and hence the region immediately in front of the PCM is not so accessible as it was in the classic Wiener experiment. We have therefore used the experimental setup shown in Fig. 1 to determine the relative phase between the incident and phase-conjugate fields through the use of a Michelson interferometer. In effect, the interference pattern formed in front of the PCM is projected into the half-space to the left of the beam splitter, and the intensity of a small region of this intensity pattern is measured by the photodetector. The properties of interferometers containing PCM's have also been discussed by other workers.[3,4]

At a conceptual level, our experiment involves introducing a variable phase delay into the incident beam in a region (A in Fig. 1) and observing that the position of the interference fringes does in fact depend on the phase of the field incident upon the PCM, as predicted by the theory of Ref. 1. This experiment is then repeated with the PCM replaced by an ordinary metal mirror, and the interference pattern is found to be independent of the phase of the incident optical wave, as was the case in the classic experiment of Wiener. We have also performed experiments in which the phase ϕ of the phase-conjugate reflectivity μ is varied, and again we have found that the interference pattern measured by the photomultiplier depends on ϕ as predicted by the theory presented in Ref. 1.

The experimental setup is shown in greater detail in Fig. 2. All the optical waves are derived from an argon-ion laser operating at a wavelength of 488 nm in a single transverse and a single longitudinal mode. Beam splitters are used to produce forward- and backward-going pump waves of complex amplitudes A_1 and A_2, respectively, and of approximately equal intensities, and to produce a weak beam of amplitude A_4, which acts as the signal beam. These beams interact in the nonlinear optical medium to generate the phase-conjugate beam whose complex amplitude we denote by A_3. The nonlinear optical material is fluorescein-doped boric-acid glass.[5] This material has a strong absorption feature centered at 437 nm, which resonantly enhances the nonlinear susceptibility describing the DFWM process. The sample used in our experiment has a thickness $L = 150$ μm and a fluorescein number density of approximately 10^{16} molecules/cm^3. The intensities of the interacting waves are kept well below the saturation intensity of the material, which at the laser wavelength is approximately 800 mW/cm^2. In this limit, the nonlinear coupling can be described by a third-order susceptibility $\chi^{(3)}$, which for our sample has a modulus of 3.8×10^{-3} esu. The internal transmission of the sample is greater than 95%, and hence to a good approximation absorption effects need not be considered in the theoretical description of our experiment. The phase-conjugate reflectivity $\mu = A_3/A_4^*$ for a PCM based on DFWM in a lossless Kerr medium is given, in the limit of a sufficiently short medium, (where $|\mu|^2 \ll 1$), by[6]

$$\mu = \frac{-12\pi i\omega}{nc}\chi^{(3)}A_1A_2L. \tag{1}$$

It should be noted that the phase of μ can be varied by changing the phase of either or both of the pump waves. In our experiment, pump-beam intensities as large as 200 mW/cm^2 were used, leading to values of $|\mu|$ as large as 0.01.

For the various experiments reported below, a variable phase retarder is placed at any of the positions marked A–F in Fig. 2. The variable phase retarder is a gas cell of 5-mm thickness containing air at a pressure between that of vacuum and atmosphere. Our experimental procedure consists

0740-3224/87/081266-03$02.00

Instabilities and Chaos in the Polarizations of Counterpropagating Light Fields

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(Received 6 April 1987)

We show that the polarizations of counterpropagating light waves in an isotropic Kerr medium are temporally unstable when their total intensity exceeds a certain threshold value. Periodic and chaotic temporal behavior can occur in the output polarizations and under certain conditions also in the output intensities.

PACS numbers: 42.20.Ji, 42.50.Tj

Intense counterpropagating laser beams are required for the operation of useful nonlinear optical interactions such as optical bistability and phase conjugation by degenerate four-wave mixing. However, recent theoretical work has indicated that there exist regimes in which such fields are not stable. Silberberg and Bar-Joseph[1] have predicted that in the scalar approximation, counterpropagating waves interacting in a nonlinear Kerr medium characterized by noninstantaneous response can undergo oscillatory and chaotic temporal evolution. This instability results from the gain of a four-wave mixing process and the distributed feedback that results from scattering off the grating formed by the interference of the counterpropagating waves; most other examples of chaos in nonlinear optics have required external feedback.[2] Theoretical studies have also recently shown that the steady-state polarizations of counterpropagating fields in a nonlinear Kerr medium can be multivalued[3] as well as possessing a chaotic *spatial* distribution.[4] Kaplan[5] has shown that for an isotropic nonlinear Kerr medium there exist in steady state four eigenarrangements for the polarizations that remain invariant upon propagation through the material. Wabnitz and Gregory[6] have pointed out that only two of these eigenpolarizations are *spatially* stable in steady state; the stable arrangements are those with both fields linearly polarized with parallel polarizations and both fields circularly polarized and corotating. Preliminary numerical simulations of the temporal behavior of this system have been conducted,[7] but to our knowledge no one has previously investigated the temporal stability of these spatially stable eigenpolarizations.

In this Letter we examine the temporal stability of the polarizations and intensities of counterpropagating waves in an isotropic Kerr medium for the case in which the input polarizations are one of the eigenarrangements that are known to be spatially stable.[6] For definiteness, we concentrate on the case in which the two input polarizations are linear and parallel.[8] We allow the field amplitudes to be time dependent and allow the medium to possess a noninstantaneous response. We find that when the input intensities exceed a certain threshold value the output beams become temporally unstable. This instability can lead to abrupt switching of the state of polarization of the output beams or can produce oscillatory or chaotic fluctuations of the output polarizations and under some circumstances also of the intensities.

We consider the geometry shown in the inset to Fig. 1. The total complex electric field in the medium can be decomposed into its x and y Cartesian components as

$$\mathbf{E}=[E_x(z,t)\hat{\mathbf{x}}+E_y(z,t)\hat{\mathbf{y}}]e^{-i\omega t}. \quad (1)$$

Each component consists of a forward- and backward-

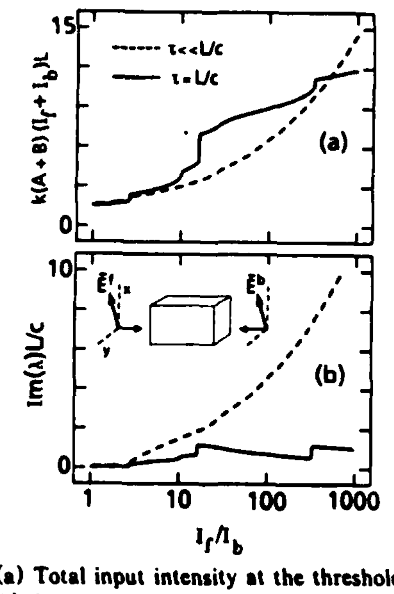

FIG. 1. (a) Total input intensity at the threshold for instability and (b) frequency of oscillation plotted as functions of the forward-to-backward input intensities for $\tau=L/c$ and for $\tau \ll L/c$. Oscillatory instabilities are predicted for input ratios greater than 2.7.

Reprinted from Optics Letters, Vol. 12, page 753, September 1987.

Optical emission from impurities within an epitaxial-silicon optical waveguide

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Received March 20, 1987; accepted June 15, 1987

Beryllium pairs form an isoelectronic complex in crystalline silicon that can bind an exciton. At sufficiently low temperatures, this bound exciton radiates in a narrow line near the wavelength $\lambda = 1.15$ μm. We report the observation of optical confinement of this bound-exciton emission from beryllium impurities introduced, by ion implantation, into an epitaxial-silicon optical waveguide.

The widespread use of silicon in microelectronics makes the notion of using silicon for integrated optics an attractive one. This is not a new idea, as a number of efforts in this direction have already met with some success, both for individual components and for complete systems. Several authors have reported schemes for making various kinds of optical waveguides in or on crystalline silicon: graded-index waveguides,[1] epitaxial waveguides,[2] and antiresonant reflecting waveguides[3,4] as well as those formed by depositing glass or other materials onto an oxidized silicon substrate.[5,6] Silicon-based integrated optical systems such as wavelength demultiplexers[7] and spectrum analyzers,[8] and others,[9] have also been described in the literature.

A recent paper by Soref and Lorenzo[2] described the performance, at sub-band-gap wavelengths, of epitaxial-silicon optical waveguides grown on silicon substrates. The guiding layer is formed by growing a lightly n-doped silicon layer upon a heavily n-doped (n^+) silicon substrate. The high density of carriers reduces the index of refraction of the substrate below that of the epitaxial layer, thus creating an optical waveguide configuration. One interesting application for such a waveguide involves the confinement of light emitted within the waveguide layer. This mechanism is widely used in direct-band-gap, III–V semiconductor emitters, but, to the best of our knowledge, it has not been explored in silicon. We report in this Letter the observation of optical confinement of sub-band-gap radiation emitted by impurities introduced into an epitaxial-silicon optical waveguide.

Since silicon is an indirect-band-gap material, it does not support the direct, band-to-band, electronic transitions that are exploited in III–V devices. For these experiments, then, we turn to a different mechanism: impurity luminescence. It is well documented that beryllium pairs form an isoelectronic impurity complex in silicon that can bind an exciton.[10–12] The radiative decay of this bound exciton (BE) gives rise to a narrow (~0.5-nm-wide) emission line near the wavelength $\lambda = 1.15$ μm, as shown in Fig. 1. This emission line is most intense at the relatively low temperature $T \sim 40$ K, and the emission persists to approximately $T = 80$ K.[12] Other such impurity centers in silicon, such as the sulfur-related complex reported earlier by two of us,[13] exhibit stable emission at higher temperatures, but their composition is much less well understood, at this point, than is that of the beryllium impurity center. The beryllium complex is ideal for the present experiments, for which thermal considerations are not really an issue, by virtue of its narrow spectrum, efficient emission (external efficiency of about 1%), and relative ease of formation. Such impurities can be

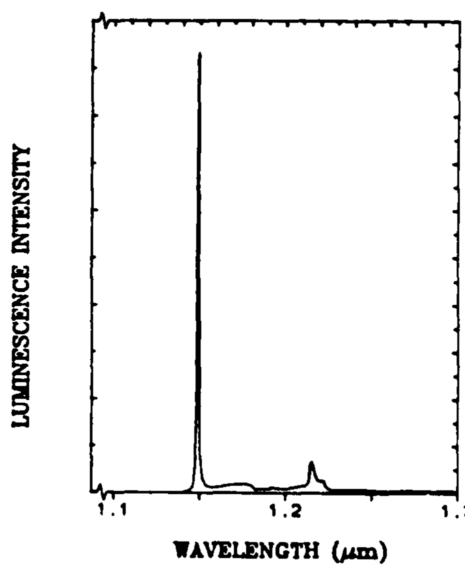

Fig. 1. Narrow spectral line emitted in the radiative decay of excitons bound to isoelectronic beryllium pairs in crystalline silicon ($T = 35$ K).

A-6

Optical waveguides in oxygen-implanted buried-oxide silicon-on-insulator structures

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(Mailed for publication in the Applied Physics Letters on 21 April 1987)

Silicon-on-insulator structures fabricated using oxygen ion implantation techniques are analyzed for their optical waveguiding properties. It is shown that TE mode waveguiding is possible with losses as low as 0.1 dB/cm. These devices hold promise for chip level interconnection, integration with silicon-based electronics and also as integrated optic polarizers.

Buried-oxide silicon-on-insulator (SOI) technology is currently being developed to meet the needs of the silicon microelectronics industry. This technology makes use of a single-crystal silicon layer separated from a conventional silicon substrate by a thin layer of silicon dioxide. Much of the interest in such structures stems from the need for electronic circuits that are resistant to radiation effects, but the degree of device isolation possible on these substrates might also offer advantages for future use in silicon VLSI.[1,2] We point out, in this letter, that the basic, buried-oxide, SOI structure that represents the state-of-the-art for this technology is also an ideal waveguide for use in Integrated Optics. As we show below, the silicon layer can function as an optical waveguide with acceptably low losses (≤ 1 dB/cm for wavelength $\lambda = 1.3\,\mu m$) even for a silicon-dioxide layer thickness of only a few tenths of one micron, which is a fraction of the oxide thickness required in other silicon-based waveguide structures. Used in this way, the SOI structure might very well find use in optical interconnect technology, and prove to be useful in truly integrated optical and electronic circuits.

One interesting approach to fabricating the SOI structure shown in Fig. 1 makes use of oxygen ion implantation into semiconductor-grade silicon. The buried oxide is formed by implanting a high dose ($\approx 10^{18}$ ions/cm^2) of oxygen ions at an energy of 150–200 keV into a silicon substrate held at a temperature in the range $450 < T < 600°C$. The elevated substrate temperature serves to maintain the crystallinity of the resulting silicon overlayer. Izumi coined the term SIMOX, Separation by IMplanted OXygen, to describe this process.[3]

cover	Air	$n_4 = 1.0$
t_3	Si	$n_3 = 3.5$
t_2	SiO_2	$n_2 = 1.5$
substrate	Si	$n_1 = 3.5$

FIG. 1. Waveguide schematic of oxygen implanted buried-oxide silicon-on-insulator (SOI) structure.

Post-annealing at a temperature $T > 1250°C$ consolidates the implanted oxygen into a buried-oxide layer of thickness $t_2 \approx 0.4\,\mu m$ covered by a crystalline Si overlayer of thickness $t_3 \approx 0.3\,\mu m$.[4] The thickness of this silicon layer can, of course, be increased by a subsequent epitaxial growth, as discussed by Lam.[5]

The analysis to determine the modes supported by the structure shown in Fig. 1 is straightforward. A wavelength $\lambda = 1.3\,\mu m$ is assumed throughout this letter, but other sub-bandgap wavelengths could be used with similar results. We also assume the illustrative values $n_2 = 1.5$ and $n_3 = 3.5$ for the refractive indices of the SiO_2 and Si, respectively.

The electric field for a TE-mode supported by the structure shown in Fig. 1 has the form

$$\mathbf{E} = \hat{y} f(x) \exp[i(\beta z - \omega t)] \tag{1}$$

where $\hat{y}$ is a unit vector and $\beta = 2\pi N/\lambda$ is the propagation constant. For the range of parameters considered here, the effective index N is complex, with $\mathrm{Re(N)} < 3.5$. This means that the waveguide mode is "substrate-leaky", corresponding to a field profile which exponentially decays along propagation axis z, and simultaneously exponentially grows into the silicon substrate layer. Of course, a waveguide field profile that grows toward $-\infty$ cannot satisfy Maxwell's equations if the waveguide is infinite in extent. For this reason, the field profiles of these "substrate-leaky" modes that we present in our figures are shown near the waveguiding and core regions. The attenuation that results from this "leakage" into substrate is obtained from $\mathrm{Im}(\beta)$. To examine this issue, we have solved the usual, four-medium, waveguide dispersion relation to obtain Re(N), the mode power attenuation $2\mathrm{Im}(\beta)$, and the field profile $f(x)$ for the TE_0 mode of the structure shown in Fig. 1. We present results for two representative choices for the Si-layer thickness: $t_3 = 0.2\,\mu m$ and $t_3 = 0.4\,\mu m$.

Fig. 2 shows the dependance of Re(N) (solid line, left vertical axis) and the attenuation (dashed line, right vertical axis) on the SiO_2 layer thickness t_2 for the TE_0 mode when the waveguiding Si layer is only $0.2\,\mu m$ thick. $\mathrm{Re(N)} \approx 2.92$ over the full range of oxide thickness shown, $0.1\,\mu m < t_2 < 0.7\,\mu m$, but the attenuation varies by six orders of magnitude over the same range in t_2. The 1 dB/cm benchmark occurs for an oxide

Hyperfine Interactions 00 (1987) HF100038

COMPETITION BETWEEN FOUR-WAVE MIXING AND AMPLIFIED SPONTANEOUS EMISSION

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There has recently been considerable interest in nonlinear optical interactions in which two different processes compete with one another. In this paper, we review some recent work in this area, and describe the results of our own investigation of competition between four-wave mixing and amplified spontaneous emission. We find that under two-photon excitation of the sodium 3d level, new optical frequency components can be generated either by amplified spontaneous emission at the 3d → 3p transition frequency or by a resonantly enhanced four-wave mixing process. We have observed competition between these two processes, resulting in the suppression of amplified spontaneous emission. The transfer of population to the 3d level is inhibited by the destructive interference between two different pathways connecting the ground and upper levels.

1. Introduction

In many optical systems, several different nonlinear optical processes can occur simultaneously; typically these processes do not evolve independently but tend to compete with one another in a complex and highly nonlinear manner. One of the earliest examples of competition effects in nonlinear optics is the competition that occurs between different stimulated scattering processes. Kaiser and Maier [1] noted that in a nonlinear material such as carbon disulfide, both stimulated Raman scattering and stimulated Brillouin scattering can occur. However it has been observed that for relatively long excitation pulses only stimulated Brillouin scattering occurred, whereas for a relatively short excitation pulse only stimulated Raman scattering occurred. The mechanism responsible for this competition was that the Brillouin gain in steady state is larger than the gain for stimulated Raman scattering, allowing the Brillouin signal to grow more rapidly and deplete the energy of the pump beam, which prevents the stimulated Raman scattering from occurring. In contrast, in the limit of short-pulse excitation, the transient gain for the Raman process is higher which does not allow the stimulated Brillouin scattering to build up.

In this paper we report on our work on competition between amplified spontaneous emission and the four-wave mixing (FWM) process [2,3]. In our experiment we tuned a dye laser to the 3d → 3d two-photon-allowed transition in atomic sodium vapor and under a broad range of experimental conditions

Submitted to Physical Review A

Quantum Theory of Rabi Sideband Generation by Forward Four-Wave Mixing

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The predictions of a quantum mechanical theory of forward four-wave mixing in a homogeneously broadened system of two-level atoms are presented. In the limit of a very short interaction region, the predictions of this theory reproduce those of well known theories for the spontaneous emission spectrum of an atom in the presence of an intense laser field. More generally, the theory predicts how the emission spectrum is modified due to propagation effects for a medium of arbitrary length. For long propagation pathlengths, the emitted radiation can be quite intense and has a spectrum that is strongly peaked at the Rabi sidebands of the incident laser frequency. The theory shows that Rabi sideband generation in the forward direction can be understood as parametric amplification of weak radiation emitted spontaneously at the Rabi sidebands. The quantum noise that initiates the four-wave mixing process has contributions both from fluctuations in the incident vacuum radiation field and from fluctuations in the polarization of the atomic dipoles. Both contributions are important for the case of a radiatively broadened medium, although the material fluctuations make the dominant contribution for the case of a medium in which the broadening is largely collisional. Under certain conditions large amounts of squeezing in the radiated field is predicted.

(November 24, 1987)

Laser Instabilities

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Abstract

Twenty-five years after the invention of the laser the basic theoretical understanding of the nature of operation of the device is a very active area of research. The reasons for this new research are the realization that recent developments in the study of nonlinear differential equations can cast new light on some old problems in laser theory, and the realization that lasers are in many ways the ideal systems in which to study bistability, chaos, and nonlinear dynamics. In this paper we will review the basics of laser theory, see what some of the new developments have been, and look at some particular recent experiments using ring dye lasers.

To be published in Proceedings of the Twelfth International Nathiagali Summer College on Physics and Contemporary Needs, Nathiagali, Pakistan, 18 June - 9 July 1987.

Transients in the Micromaser

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Abstract

The Jaynes-Cummings model of a single two-level atom interacting with a single field mode of a lossless cavity is the central problem of quantum optics. In the past 25 years more than a thousand theoretical papers have been written exploring various aspects of this model. Recently an accurate experimental realization of this ideal model has been achieved in the laboratory. The implications of this new experimental capability are discussed, and new experiments are proposed that can explore the transient absorption and emission of a single photon by a single atom in a high Q cavity.

To be published in Proceedings of the Twelfth International Nathiagali Summer College on Physics and Contemporary Needs. Nathiagali, Pakistan, 18 June - 9 July 1987.

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Mol. Cryst. Liq. Cryst., 1987, Vol. ?, pp. 000–000
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Near-Infrared Dichroism of a Mesogenic Transition Metal Complex and its Solubility in Nematic Hosts

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(*Received October 8, 1987*)

A transition metal complex possessing the nematic phase, bis (*p-n*-butylstyryl-1, 2-dithiolato) nickel, was synthesized and its optical properties and solubility in the nematic hosts K15 and MBBA were investigated. The metal complex displayed a high solubility in both host materials (up to 10% wt/wt) and a strong near-infrared absorption band centered at 860 nm. A blocking extinction of greater than OD = 3 was obtained with a 100 micron pathlength of a 0.5% wt/wt mixture of the nematic metal complex in K15, suggesting its usefulness for passive blocking of near-infrared radiation. A 24 micron thick, homogeneously aligned guest-host cell containing a 1% wt/wt mixture of the metal complex in K15 possessed a contrast ratio of nearly 5:1 and a blocking extinction of OD = 3.5 at 860 nm, demonstrating for the first time the existence of near-infrared dichroism in this class of materials. The solubility and blocking extinction of the mesogenic metal complex in K15 was considerably superior to the non-mesogenic near IR laser dye bis(dimethylaminodithiobenzil) nickel in the same host. An interaction of the nematic metal complex in mixtures with MBBA which resulted in the creation of a new absorption band at 1050 nm was also observed.

I. INTRODUCTION

The use of dichroic dyes in guest-host liquid crystal displays has received a great deal of attention in recent years. Numerous literature references[1-7] can be found regarding the order parameter, dichroism, solubility, and stability of a wide variety of dyes in nematic and smectic hosts for electro-optical applications in the visible region of the spectrum. Little information is available, however, regarding applications in the near-infrared region of the spectrum,[8] such as the blocking or modulation of diode or YAG laser sources. One reason for this lack

A-12

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A REEXAMINATION OF THE SYNTHESIS OF LIQUID CRYSTALLINE SIDE-CHAIN POLYACRYLATES VIA LIQUID-LIQUID PHASE TRANSFER CATALYSIS

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ABSTRACT

We have reexamined the synthesis of liquid crystalline side-chain polyacrylates under liquid-liquid phase transfer conditions as first reported by Keller. Instead of the polymeric liquid crystals, the hydrolysis of the mesogen and a subsequent nucleophilic substitution reaction were found to predominate over the anticipated reaction between carboxylate group and the mesogen. The present results are consistent with the high pH conditions prevailing in the poly(sodium acrylate) solution as determined previously. The control of the pH value in the reaction medium is perceived to be crucial in determining the reaction pathway.

SUBMITTED TO MACROMOLECULES

THE PREPARATION OF LIQUID-CRYSTALLINE SIDE-CHAIN POLYACRYLATE BY CHEMICALLY MODIFYING POLY(SODIUM ACRYLATE) IN HEXAMETHYLPHOSPHORAMIDE

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ABSTRACT

A new reaction scheme has been worked out for the synthesis of liquid crystalline side-chain polyacrylate based on the chemical modification of poly(sodium acrylate) with a mesogen in hexamethylphosphoramide. The polymer product was characterized by IR and NMR spectroscopy for chemical structure, by GPC for molecular weight and its distribution, and by DSC and optical microscopy for thermotropic behavior.

Above-Threshold Ionization With Femtosecond Pulses: A Comparision of Quantum and Classical Predictions

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We present numerical solutions of the three-dimensional Schrödinger's and Newton's equations describing a hydrogen atom undergoing above-threshold ionization by an optical femtosecond laser pulse. A clear classical correspondence is found. Various splittings and shifts of the ATI spectral peaks are observed, and are shown to be due to the bound-state structure of the atom.

Submitted to: Physical Review A

Transient Absorption by a Rydberg Atom in a Resonant Cavity

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A theoretical analysis is presented describing the interaction of the field in a high-Q microwave cavity with an atom that is suddenly excited to the lower of two Rydberg levels that are resonantly coupled by the field. It is found that the field initially in the cavity is cancelled by interference with the source field emitted by the atom. The absorption may be characterized as a "darkness wave packet" emitted by the atom and reflected by the cavity walls.

Submitted to Physical Review A

AMPLITUDE-STABILIZED CHAOTIC LIGHT

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ABSTRACT

Large-bandwidth laser light pulses with pure frequency fluctuations have been generated. Chaotic light pulses from a cavityless dye laser are temporally smoothed by passing them through strongly saturated amplifiers. Since the amplification process does not change the phase of the amplified light, the output radiation has the well defined phase fluctuations of chaotic light, yet essentially no amplitude fluctuations.

SIGNAL PROCESSING & IMAGE UNDERSTANDING

Sine–cosine cascade correlator with real-valued filters

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Received December 19, 1986; accepted February 22, 1987

A novel sine–filter–cosine cascade is proposed that is realizable for either coherent or spatially incoherent illumination. Computer simulation is used to demonstrate effectively matched filter performance and elimination of deleterious background bias.

Optical matched filtering for coherently illuminated objects was described first by Vander Lugt.[1] Extension to incoherently illuminated objects was proposed by Lohmann[2] and studied by many others. Spectrally broadband illumination that is spatially incoherent was used with holographically produced matched filters in more recent experiments by George and Morris.[3] New concepts in correlation types of Fourier-plane filters include the phase-only filter[4] and the synthetic-discriminant-function filter.[5]

In the literature one finds discussions and practical optical realizations for two-dimensional sine, cosine, Hartley, and Fourier transforms, including both incoherently and coherently illuminated cases.[6-9] With the restriction that the input object be real valued, which is reasonable for pictorial imagery, and the use of transforms that are real valued, it is plausible to search for correlation filters that are real valued and whose performance in signal-to-noise ratio is essentially that of a spatial matched filter. The results of this search are the subject of this Letter, and we describe two new correlator systems that meet both of these goals. Moreover, in one of these novel correlators we find additionally that we can eliminate a bias output that is nonspecific with respect to object recognition.

First, we briefly describe some basic properties of the cosine transform $F_c(u, v)$ and the sine transform $F_s(u, v)$ of the general function $f(x, y)$. Letting (u, v) correspond to the transform variables of (x, y), we write the transform definitions:

$$F_c(u, v) = \iint_{-\infty}^{\infty} \mathrm{d}x\mathrm{d}y f(x, y)\cos[2\pi(ux + vy)], \quad (1)$$

$$F_s(u, v) = \iint_{-\infty}^{\infty} \mathrm{d}x\mathrm{d}y f(x, y)\sin[2\pi(ux + vy)]. \quad (2)$$

When $f(x, y)$ is real valued, then F_c and F_s are real-valued functions of the real variables (u, v). The symmetry properties of the sine and cosine transforms are of particular interest and are listed in Table 1. For real valued $f(x, y)$, we define the even part $f_e(x, y)$ and the odd part $f_o(x, y)$ as follows:

$$f_e(x, y) = [f(x, y) + f(-x, -y)]/2,$$
$$f_o(x, y) = [f(x, y) - f(-x, -y)]/2.$$

Briefly, we note that a sine transform operating on the real-valued $f(x, y)$ filters out f_e and provides an output depending only on the odd portion f_o, and correspondingly a cosine transform filters out f_o and retains f_e.

Consider the three transform-correlation systems shown in Fig. 1, noting that the Hartley transform $F_h(u, v)$ of the function $f(x, y)$ is defined by

$$F_h(u, v) = \iint_{-\infty}^{\infty} \mathrm{d}x\mathrm{d}y f(x, y)[\cos 2\pi(xu + yv) + \sin 2\pi(xu + yv)]. \quad (3)$$

Each has (I) an input plane (x, y), (II) a filter plane (u, v), and (III) an output plane (x, y). Let $g(x, y)$ be a real-valued reference function, and denote its various transforms as follows: cosine G_c; sine G_s; Hartley G_h; and Fourier G. For the Fig. 1(a) matched-filter system, it consists of a spatial Fourier transform, a filter $G^*(u, v)$, an inverse Fourier transform, and an output plane. Similarly, in Fig. 1(b), we show a cascade of a spatial Hartley transform, a filter $G_h(u, v)$, a cosine transform, and output. Finally, in Fig. 1(c), we cascade a sine transform and a filter G_s, followed by a cosine transform and an output plane.

Now, in each system let the input function in plane (I) be $f(x, y)$. After a straightforward calculation, one can show that the output signal for the system in Fig. 1(a) is given by

$$v_3(x, y) = \iint_{-\infty}^{\infty} \mathrm{d}x'\mathrm{d}y' f(x', y')g^*(x' - x, y' - y). \quad (4)$$

When the input function, $f(x, y)$, becomes g, then by Eq. (4), the output of the matched-filter system is simply the autocorrelation of g, denoted by $g \star g$.

In Fig. 1(b) the output signal $v_3(x, y)$ is given in general by

$$v_3(x, y) = \iint_{-\infty}^{\infty} F_h(u, v)G_h(u, v) \times \cos[2\pi(xu + yv)]\mathrm{d}u\mathrm{d}v. \quad (5)$$

The correlation property of the system in Fig. 1(b) is readily seen by letting f go to g. From Eq. (5), using

Table 1. Symmetry Properties of the Cosine and Sine Transforms

Function	Sine Transform, F_s	Cosine Transform, F_c
$f(x, y)$	Odd in (u, v)	Even in (u, v)
$f_o(x, y)$	Odd	0
$f_e(x, y)$	0	Even

A-18

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Diffraction from a circular aperture: on-axis field strength

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A useful, analytical result for the on-axis field strength from a uniformly illuminated circular aperture is derived. Also, new calculations for circular apertures with tapered illuminations are presented.

I. Introduction

At specific distances from a circular aperture illuminated by a monochromatic plane wave the on-axis intensity exhibits distinct maxima and minima. This phenomenon is explained in standard optics texts by counting the number of nearly equal area Fresnel half-period zones subtended by the aperture.[1,2] When the number of zones is even, there is a minimum; when the number of zones is odd, there is a maximum. This explanation is adequate for describing the on-axis field strength in the Fresnel region. However, in the near-field, i.e., in the region between the aperture and the Fresnel region, one must take into account the unequal areas of the half-period zones as well as their unequal contributions due to varying distance from the axis and obliquity.

From a theoretical standpoint the calculation of the on-axis field is dependent on the model chosen for the aperture and the assumptions made regarding the aperture field. Over the years there has been a fair amount of discussion and research concerning the validity of various scalar diffraction integrals, comparing results based on Maxwell's equations, and regarding the physical reality of different aperture models. The interested reader should consult the summary of early theoretical calculations and comparisons to experimental data compiled by Bouwkamp[3] and other more recent work.[4,5] We do not wish to engage in this discussion except to summarize as follows. If one makes the idealization of a circular aperture of radius a in a thin, perfectly conducting plane screen, one can write an exact solution of Maxwell's equations for the aperture and right half-space fields formally for an arbitrary radius a and explicitly for $a < \lambda/2$. However, for an absorbing screen with an aperture, the boundary conditions are not specified exactly, and one cannot claim a rigorous solution.

In this paper we derive a useful, analytical result valid in the right half-space for the on-axis field strength from a uniformly illuminated circular aperture in a perfectly conducting screen. We also present new calculations applicable to circular apertures with tapered illuminations. These results should be useful for applications involving short-distance illumination of targets and objects, determination of radiation hazards from high-powered aperture antennas, and the measurement of antenna gain.

II. Diffraction Integrals

The diffraction geometry is illustrated in Fig. 1. An infinitely thin, perfectly conducting plane screen containing an aperture A is placed in the x,y plane at $z = 0$. The electric field $\mathbf{E}(\mathbf{r})$ in the right half-space, i.e., $z \geq 0$, is then uniquely specified by the tangential component of the exact electric field in the aperture[3,6,7]:

$$\mathbf{E}(\mathbf{r}) = \frac{1}{2\pi} \nabla \times \iint_A \mathbf{n} \times \mathbf{E}(\mathbf{r}') \frac{\exp(ikR)}{R} dx'dy', \tag{1}$$

where

$$R = |\mathbf{r} - \mathbf{r}'| = \sqrt{(x - x')^2 + (y - y')^2 + z^2},$$

$\exp(ikR)/R$ is the free-space Green's function, $\mathbf{n}$ is a unit normal pointing in the $+z$ direction, and $\mathbf{E}(\mathbf{r}')$ is the exact electric field in the aperture. The integration extends only over the aperture because the screen is a perfect conductor. An $\exp(-i\omega t)$ time dependence is implicitly assumed.

As an approximation to the exact electric field in the aperture, we assume that we may replace $\mathbf{E}(\mathbf{r}')$ with $\mathbf{E}^{\mathrm{inc}}(\mathbf{r}')$. This substitution in Eq. (1) yields

$$\mathbf{E}(\mathbf{r}) = \frac{1}{2\pi} \nabla \times \iint_A \mathbf{n} \times \mathbf{E}^{\mathrm{inc}}(\mathbf{r}') \frac{\exp(ikR)}{R} dx'dy'. \tag{2}$$

This approximation is reasonable for apertures that are much larger than a wavelength.

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Received 26 November 1986.
0003-6935/87/122360-04$02.00/0.

THE INSTANTANEOUS CROSS-SPECTRAL DENSITY OF NON-STATIONARY WAVEFIELDS *

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Received 7 January 1987

The concept of instantaneous cross-spectral density of a non-stationary ensemble of wavefields is introduced and differential equations are derived that govern its propagation in free space. The equations can be used to obtain information about the manner in which the instantaneous spectrum (of the Wigner-type) of an ensemble of pulses changes on propagation.

1. Introduction

Although much research is currently being carried out regarding the generation and utilization of very short light pulses (of the order of femto-seconds) very little is known about the evolution of their spatial and temporal characteristics on propagation. Even the concept of the spectrum of such pulses has not been satisfactorily clarified; in fact a number of different definitions of instantaneous spectra of pulses have been proposed [::1] but little is known about how the spectra change as the pulse propagates.

In the present note we introduce the concept of instantaneous cross-spectral density of an ensemble of non-stationary fields which, in a sense, is a generalization of one of the definitions of the instantaneous spectrum (of the Wigner type) that has been sometimes used in connection with time-frequency analysis of electrical, acoustical or optical signals [2–8]. We show that for fields in free space, the instantaneous cross-spectral density obeys two second-order differential equations. From solutions of these equations one may deduce how the instantaneous spectrum of the field changes on propagation.

2. The instantaneous spectrum of a random signal

Let us first consider a complex stationary random signal $V(t)$ of zero mean

$$\langle V(t)\rangle = 0 . \tag{2.1}$$

Here the angular brackets denote the ensemble average. The spectral density (spectrum) of $V(t)$ may be defined by the usual formula

$$S(\omega) = \lim_{T\to\infty}\left\langle \frac{1}{2T}\left|\int_{-T}^{T} V(t)\exp(i\omega t)\,dt\right|^2\right\rangle . \tag{2.2}$$

We will denote by $R(\tau)$ the autocorrelation function of $V(t)$, viz.

$$R(\tau) = \langle V^*(t)\, V(t+\tau)\rangle . \tag{2.3}$$

According to the Wiener-Khintchine theorem $S(\omega)$ and $R(\tau)$ form a Fourier transform pair:

* Work supported by the U.S. Army Research Office.
[1] Also at the Institute of Optics, University of Rochester.
[::1] References to some of the pertinent lineratures are given in refs. [1] and [8].

Reprinted from Optics Letters, Vol. 13, page 4, January 1988.

Spectral shifts produced by source correlations

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Received July 31, 1987; accepted October 16, 1987

Statistical correlations of the light emitted by a partially coherent source can produce frequency shifts in the spectrum observed in the far field if the correlation function of the emitted radiation does not satisfy a certain scaling law. A Fourier achromat is used to generate a secondary source in which the degree of spectral coherence is independent of wavelength; i.e., it violates the scaling law. The spectrum detected in the far zone of the secondary source is, in general, found to be displaced in frequency and distorted relative to the spectrum measured at the secondary source. The displacement can be toward the higher frequencies or the lower frequencies depending on the direction of observation.

The spectrum of light emitted by a partially coherent source depends on the degree of spectral coherence across the source. If the source is planar, secondary, and quasi-homogeneous and if the degree of spectral coherence at the source satisfies a certain scaling law,[1] then the normalized spectrum of light is the same throughout the far zone and is equal to the normalized spectrum at the source. The source is said to satisfy the scaling law if the complex degree of spectral coherence depends on the wavelength only through the variable $k(\mathbf{r}_2 - \mathbf{r}_1)$, where $(\mathbf{r}_2 - \mathbf{r}_1)$ denotes the (vectorial) distance between two points on the source, $k = 2\pi/\lambda$, and λ represents the wavelength of light.

If the degree of spectral coherence does not satisfy the scaling law, the spectrum of the emitted radiation that is detected some distance away from the source will generally be different from that measured at the source. Experiments that illustrate the influence of source correlations on the spectrum of light detected in the far zone have been reported.[2]

Wolf[3-5] has shown that under certain conditions source correlations can produce frequency shifts in the observed spectrum. Recently Bocko *et al.*[6] observed frequency shifts of the field spectrum generated by two appropriately correlated acoustical sources.

In this Letter we describe experiments in which frequency shifts of the optical spectrum detected in the far field of a planar secondary source are observed. In the experiments we use a Fourier achromat to generate a secondary source with a degree of spectral coherence that is independent of wavelength and therefore does not satisfy the scaling law. The spectrum detected in the far field of the source depends on the spectrum at the source, the degree of spectral coherence at the source, and the location of the observation point.

Consider a general linear optical system with an impulse-response function given by $h(\mathbf{x}, \boldsymbol{\xi}; \nu)$, in which the vectors $\boldsymbol{\xi}$ and $\mathbf{x}$ represent points in the input and output planes, respectively, and ν denotes the illumination frequency, $\nu = c/\lambda$, where λ is the wavelength. The spectral amplitude of the system output $U_{II}(\mathbf{x}; \nu)$ may be expressed as a superposition of the input spectral amplitude $U_I(\boldsymbol{\xi}; \nu)$ and the system impulse response as follows:

$$U_{II}(\mathbf{x}; \nu) = \int U_I(\boldsymbol{\xi}; \nu)\, h(\mathbf{x}, \boldsymbol{\xi}; \nu)\, d^2\boldsymbol{\xi}. \tag{1}$$

The cross-spectral-density function is defined[7] as

$$W(\mathbf{x}_1, \mathbf{x}_2; \nu) = \langle U(\mathbf{x}_1; \nu) U^*(\mathbf{x}_2; \nu) \rangle, \tag{2}$$

in which $\langle \ldots \rangle$ denotes an average over an ensemble of sources. Two quantities of particular interest here are the spectral intensity,

$$S(\mathbf{x}; \nu) = W(\mathbf{x}, \mathbf{x}; \nu), \tag{3}$$

and the normalized cross-spectral-density function,

$$\mu(\mathbf{x}_1, \mathbf{x}_2; \nu) = \frac{W(\mathbf{x}_1, \mathbf{x}_2; \nu)}{[S(\mathbf{x}_1; \nu)\, S(\mathbf{x}_2; \nu)]^{1/2}}, \tag{4}$$

known as the complex degree of spectral coherence.

A diagram of the optical system used in the experiments is shown in Fig. 1. The illumination is provided by a quasi-homogeneous thermal source[8] that is imaged onto plane I. The two-lens imaging system between the primary source and plane I is characterized

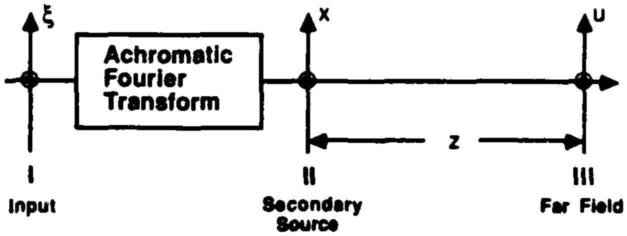

Fig. 1. Experimental configuration for realization of a secondary source with a controlled degree of spectral coherence. An object located in plane I is illuminated using a broadband, partially coherent source that obeys the scaling law. A secondary source with wavelength-independent spatial coherence is formed in plane II through application of the generalized Van Cittert–Zernike theorem. The spectral intensity is measured at the secondary source (plane II) and in the far field of the secondary source (plane III).

A-21

SPECTRAL MODULATION BY CONTROL OF SOURCE CORRELATIONS *

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Received 16 September 1987

It has recently been demonstrated both theoretically and experimentally that the spectrum of light emitted by a source can be modified by changing the correlation properties of the source. We examine the possibility of using this mechanism to modulate spectra in a desired manner. A simple configuration is considered, consisting of two small sources, emitting identical spectral lines and we show that by suitably correlating the sources one can control the width, the amplitude and the frequency of the emitted light. The possibility of generating several lines from a single one is also considered.

1. Introduction

It has been shown theoretically not long ago [1] that the spectrum of light emitted by a source depends not only on the source spectrum but also on the correlation properties of the source. This prediction has been verified by experiments [2a]. The spectral changes that may arise from source correlations may be such as to produce frequency shifts of spectral lines [3–5] either towards lower frequencies (red shifts) or towards higher frequencies (blue shifts). Such shifts have recently been demonstrated by experiments with optical [2b] and also with acoustical [6] sources.

In the present note we show that source-correlations can give rise to other interesting modifications of spectra. We consider only a simple arrangement, consisting of two small sources which generate radiation of identical spectra, and we analyze the effects of correlation between the two sources on the spectrum of the emitted radiation. We show that spectral lines can be frequency shifted, made narrower or broader and that several lines may be generated from a single line by this mechanism. These results suggest that it might be possible to develop a new technique for modulating spectra in a desired manner by control of source correlations.

* Research supported by the National Science Foundation and by the U.S. Army Research Office.

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2. Formulation of the problem

Consider light generated by two small fluctuating sources located at points P_1 and P_2. We assume that the fluctuations are statistically stationary. Let $\{Q(P_1, \omega)\}$ and $\{Q(P_2, \omega)\}$ be the ensembles that represent the source fluctuations at frequency ω. Further let $\{U(P, \omega)\}$ be the ensemble that represents the field at P, generated by the two sources (fig. 1). We assume that the spectra of the two source-distributions are identical and we denote them by $S_Q(\omega)$. More specifically

$$S_Q(\omega)=\langle Q^*(P_1,\omega)\, Q(P_1,\omega)\rangle = \langle Q^*(P_2,\omega)\, Q(P_2,\omega)\rangle,$$

where the angular brackets denote ensemble average.

White light interferometry with an achromatic phase shifter

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ABSTRACT

The principle of operation of an achromatic modulator or phase shifter is presented. Specific triangular configurations are described that consist of two base gratings and a vertex element which may be either a transmission-type hologram or an acousto-optic modulator. The application of this concept is illustrated by a generalized white light interferometer with very fine differential phase control and two separated, collinear output paths. The achromatic phase shifter is also shown to make an important improvement to the white light cosinusoidal transform hybrid. Two different configurations are presented.

1. INTRODUCTION

In AC interferometry and in optical information processing, it would be useful to have a simple passive device that provides an adjustable optical phase shift which is independent of wavelength. A grating interferometer that will produce either an adjustable phase delay that is achromatic or frequency modulation that is independent of wavelength has been described in the literature by the authors of this paper.[1] In earlier applications diffraction gratings have been used as beamsplitters in interferometers and to provide phase shifts in monochromatic light.[2-5] More recently diffraction gratings and grating interferometers have been used in white light optical information processing.[6-10]

For the SPIE talk and this paper, we will describe the application of this phase shifter to white light interferometry. The paper concludes with a description of three different interferometers. First there is a white light interferometer that provides two collimated output beams which can be differentially phase shifted by a few degrees achromatically over a very broad spectral bandwidth. The second and third interferometers are variations on sinusoidal spatial transform configurations that are also designed for operation in white light.

2. PRINCIPLE OF OPERATION OF THE ACHROMATIC MODULATOR

Here we would like to present a phenomenological explanation of the operation of the achromatic phase shifter and/or modulator. First, consider a monochromatic beam reflected by a mirror moving with a speed v_m, as in Fig. 1. When $v_m/c << 1$, the incident frequency υ is Doppler-shifted to the new frequency υ' given by

$$\upsilon' = \upsilon - 2v_m\left(\frac{\sin\theta}{\lambda}\right) . \tag{1}$$

The angle θ is the angle from the mirror surface to the ray.

If we agree at the outset that we would like to have the shift in frequency, $\upsilon' - \upsilon$, be independent of wavelength or achromatic, then we need to find a way to make the factor $[\sin\theta/\lambda]$ be independent of λ. Since this formula is "grating-like", it is a reasonable expectation that one may obtain this angular dependence $\theta(\lambda)$ with λ by means of a grating.

Proc. Soc. Photo-Opt. Instr. Eng. 883, xxx-yyy (1988).

Diffuser Radiation Patterns Over a Large Dynamic Range

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ABSTRACT

Theoretical computations are presented for the far-zone radiation patterns from strong diffusers having a normally distributed height profile and different autocorrelation functions for the surface height. Diffusers having two scales of roughness are also analyzed. Data are presented from ground-glass and acid-etched-glass diffusers using a scatterometer that permits measurements over an entire hemisphere with a dynamic range of 6 to 8 orders of magnitude. For the ground glass, excellent agreement is obtained using an autocorrelation function that is conical for small spatial offsets; this is consistent with our physical expectation based on the need for a rapid fall-off in surface correlation, due to the jagged nature of the surface relief. For the acid-etched case, excellent agreement is found using an autocorrelation function that is paraboloidal for small spatial offsets. Remote sensing of surface roughness and surface correlation are seen to be practical and accurate.

Diffraction patterns in the shadows of disks and obstacles

R. Edward English, Jr. and Nicholas George

We compare the Fresnel diffraction pattern of a thin circular disk to that of a square obstacle, specifically evaluating the on-axis field strength. Photographs of the diffraction patterns reveal some curious features for the square obstacle. Secondly, the precise electric and magnetic fields behind a conducting circular disk are evaluated without invoking the Fresnel approximation and contrasted with the rigorous electromagnetic result for a metal sphere. The calculations show that the two cases differ only slightly in the Fresnel region. In the near-field new computational results for the sphere are analyzed.

I. Introduction

Experimental observation and analytical calculation of diffraction patterns in the shadow predate the time of Fresnel and the presentation of his theory of diffraction. Mainly the research on shadow region diffraction patterns has dealt with the particular case of a circular disk. In the Fresnel approximation the diffraction pattern behind a circular disk can be computed using Lommel functions. The pattern is characterized by a concentric ring structure and a bright central spot, Poisson's spot. Early observations were reported by Hufford.[1]

Other obstacle shapes are interesting as well and produce unanticipated results. The pattern behind a square obstacle can be evaluated straightforwardly in terms of Fresnel integrals or Cornu's spiral. This type of calculation was performed by White[2] in order to understand resist images created by near-contact printing. He observed an intensity node in the center of the shadow for sufficiently large print gaps. Computer calculations based on an FFT algorithm exhibited other more striking features.[3] Kathuria and Herziger[4] performed calculations behind square annular apertures, but did not describe these unusual features. Our efforts have not uncovered detailed calculations or observations of these diffraction pattern features in the open literature, although a photograph of the pattern in the shadow of an opaque square appears in the *Atlas of Optical Phenomena*.[5] (Diffraction pattern photographs from other shapes were presented by Harris.[6] The complementary problem of Fresnel diffraction by a square aperture is described and photographically displayed in elementary optics texts.) The surprising features in the square obstacle diffraction pattern are discussed in Sec. III, and photographs clearly display them.

Rigorous electromagnetic treatments of diffraction problems are limited to a relatively small number of cases. Hence, one often resorts to some level of approximation in evaluating the diffraction pattern. In Sec. II we review applicable diffraction integrals and present careful, precise expressions suitable for computing the axial electric and magnetic fields behind large apertures and obstacles even at close distances. Essentially, these expression employ only the approximation that the aperture field may be replaced by the incident field. In Sec. IV these fields are evaluated for a large, thin, perfectly conducting circular disk without invoking the Fresnel approximation because it is not necessary.

Rigorous solutions for thin, conducting disks are known. However, the solutions are either applicable only to small disks or calculable for disks of a couple of wavelengths in diameter.[7-9] Experimental observations for the axial fields are available,[10] but again these involve small disks. As a result the precise calculations derived in Sec. IV are useful in analyzing the large, conducting disk diffraction problem.

Diffraction by a spherical particle is a basic problem of great interest and can be treated rigorously.[11-13] The fundamental nature and applicability of this problem have prompted a large amount of research, much of which involves only far-zone calculations. It is only recently that near-field calculations have been performed.[14-16] In Sec. IV new computational results are presented for the axial fields behind a large, perfectly conducting sphere.

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Submitted September 1987.

Generation and statistical properties of optical dead-time effects

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An optoelectronic device, which can generate either the nonparalyzable or the paralyzable dead-time effect, has been constructed using a feedback scheme in conjunction with the acousto-optic deflector. "Semi-classical" experiments show good agreement with the theory, which predicts antibunching and sub-Poissonian statistics. An expression for the correlation function of an arbitrary order is obtained for a general renewal process. From this general result exact expressions for autocorrelation functions for both the nonparalyzable and the paralyzable counters are derived when the dead time is greater than twice the sample time. The Fano factor is considered for both the nonparalyzable and the paralyzable counters. It is seen that the Fano factor for the paralyzable counter can be smaller than that for the nonparalyzable counter for certain range of the input count rate.

Pattern Recognition using Photon-Limited Images *

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August 1987

* Chapter in Optical Computing and Processing, H. H. Arsenault and T. Szoplik, Eds., Academic Press, New York, 1988.

Pattern Recognition using Photon-Limited Images

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Submitted to J. Opt. Soc. Amer. A.

CHANGES IN THE SPECTRUM OF PARTIALLY COHERENT LIGHT BEAM PROPAGATING IN FREE SPACE†

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ABSTRACT

The effect of spatial coherence of a source on the spectrum of the emitted light is studied for a class of beam-like fields. The source is assumed to be planar, secondary and quasi - homogeneous. We consider in detail the situation where the source spectrum is a line with a Gaussian profile and the degree of spectral coherence is characterized by a Gaussian distribution. The changes that the spectrum undergoes as the emitted light propagates from the source plane to the far zone are illustrated by computed curves. Two factors are shown to contribute to changes in the spectrum. Effects due to finite size of the source which tend to shift the emitted spectral line towards the shorter wavelengths (a blue shift) and effects due to source correlations which tend to shift the line towards longer wavelengths (a red shift). The magnitude of the resulting shift in the far zone depends on the direction of observation. These results are in qualitative agreement with recent experimental observations of D.Faklis and G.M.Morris.

OPTICAL SYSTEMS DESIGN

Submitted to Applied Optics

Radial Gradient-Index Eyepiece Design

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Masataka Shiba, David Y. H. Wang

Abstract

Three and four element eyepiece designs are presented each with a different type of radial gradient-index distribution. Both quadratic and modified quadratic index profiles are shown to provide effective control of the field aberrations. In particular, the three element design with a quadratic index profile demonstrates that the inhomogeneous power contribution can make significant contributions to the overall system performance, especially the astigmatism correction. Using gradient index components has allowed for increased eye-relief and field of view making these designs comparable to five and six element ones.

Submitted to the Journal of the Optical Society
of America A

Optical System Assessment. I

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ABSTRACT

The continuing explosion in available computing power has not reduced the importance of efficient methods of optical system assessment for automatic lens design. On the contrary, the new capabilities are simply putting light at the end of the tunnel of truly automatic optical design. It is proposed that the merit of a system assessment scheme be measured in terms of the accuracy of its estimation of the overall performance of a proposed system as a function of the amount of work done (eg. number of rays traced). Using this criterion, a number of schemes based on ray tracing are compared and some highly efficient assessment procedures are developed. The key to the most effective methods lies in coupling appropriate coordinates (selected to smooth the relevant integrands — either wavefront errors or transverse error functions) with Gaussian integration schemes. The efficiency of the resulting methods is orders of magnitude ahead of comparatively simple schemes.

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